NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

PRELIMINARY PROPELLER SELECTION USING THE WAGENINGEN B-SCREW SERIES AND A GENERAL PURPOSE NON-LINEAR OPTIMIZER

by

Michael Peter Smith II

June 1983

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This thesis presents the use of a general purpose non-linear optimization program in the preliminary stage of ship design for the selection of a propeller based on methodical series propeller test data. The propeller series utilized is the well-known Wageningen B-Series. Three (3) "Design Cases", representing the thrust, power and matching approaches to powering problems, are formulated as FORTRAN subprogram analysis codes for solution by

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Preliminary Transition Experiments Using
the Wortmann Laminar Profile and a
General Purpose Thin-Laminar Airfoil

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the synthesis/optimization program COPES/CONMIN. Designer constraints considered are:

1) diameter limitation
2) cavitation limit on expanded area ratio using Keller's criterion
3) strength requirement determined by an empirical relation and by a method developed by Schoenherr with modifications by the author.

Objective functions considered are maximized open water efficiency and minimized propeller blade weight. Optimized solutions to specific problems previously presented by other authors are obtained and results are compared.

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Preliminary Propeller Selection Using the Wageningen B-Screw Series and a General Purpose Non-Linear Optimizer

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ABSTRACT

This thesis presents the use of a general purpose non-linear optimization program in the preliminary stage of ship design for the selection of a propeller based on methodical series propeller test data. The propeller series utilized is the well-known Wageningen B-Series. Three (3) "Design Cases", representing the thrust, power and matching approaches to powering problems, are formulated as FORTRAN subprogram analysis codes for solution by the synthesis/optimization program COPES/CONMIN. Designer constraints considered are:

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> If someone says it's impossible, then, quite obviously, he has never done it.

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I. INTRODUCTION

A. BACKGROUND

The ship design process, in its most rudimentary form, has been formulated and tracked by the utilization of the classical design spiral (see Figure 1.1). The design follows a convergent helical path past each major milestone "spoke" until, after numerous iterative cycles, the final configuration is "centered" upon. Whether one attempts to segregate the principal phases of Preliminary, Advanced and Contract Design into separate spirals or combine these phases in series along the entire path to the center, it is not long before the designer's roughed-out sketches give way to serious "number crunching", specifically that of propulsion power estimation.

To estimate the power required to drive the ship through the water at its design speed, a decision must first be made as to what type of propulsor (i.e., propeller, water jet, paddle wheel, etc.) will be used. For the average case, and for the discussion that follows, the marine propeller is chosen to be the propulsion device. Since

> a ship propeller may be regarded as a transducer that converts the rotational power transmitted through the shaft into the translational power to propel the ship, [Ref. 18: p. 10]

the selection and design of this device is obviously an important factor in the eventual size (weight and power) of the ship's propulsion plant. While hydrodynamicists provide

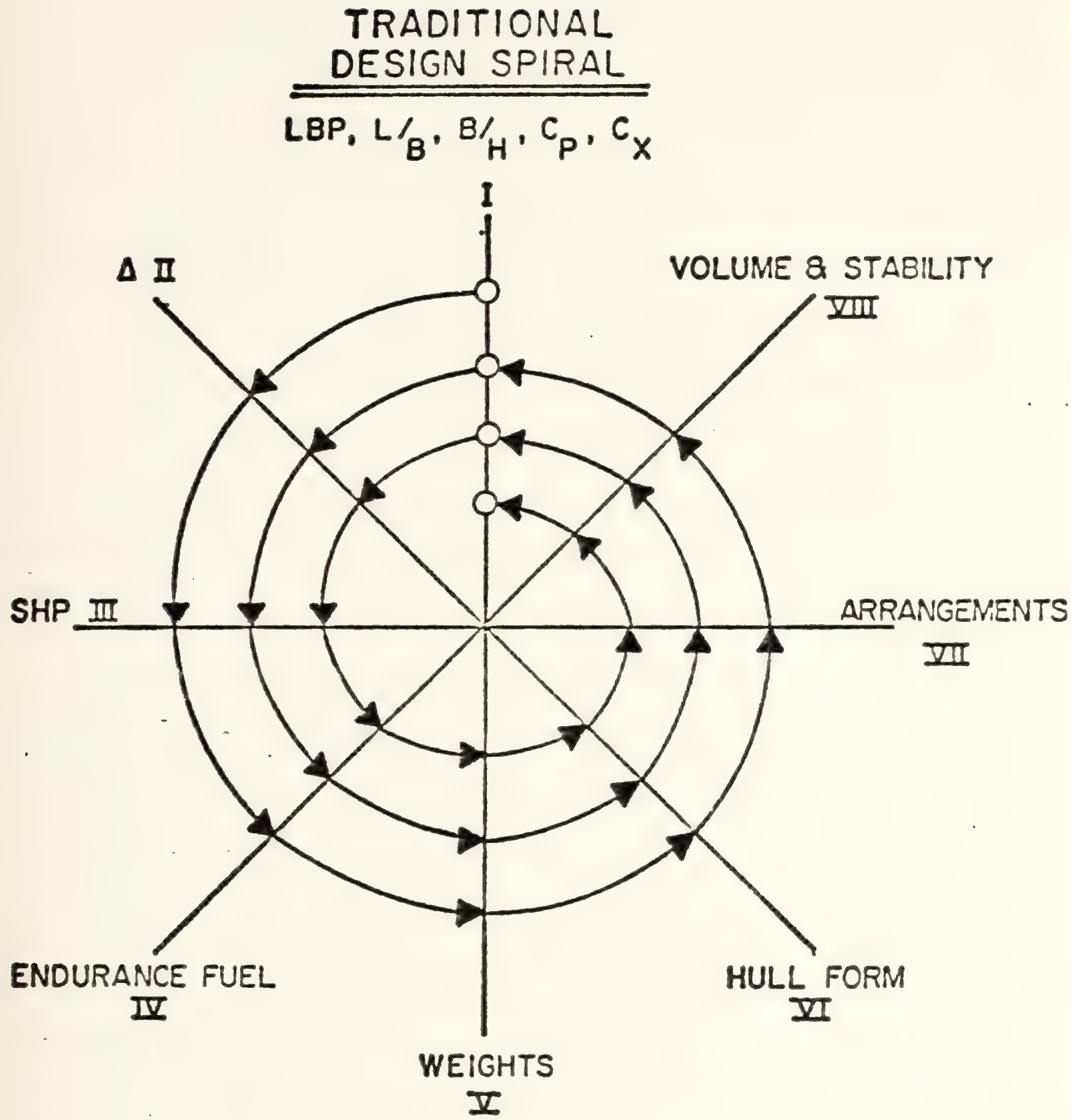

Figure 1.1 Traditional Design Spiral

a myriad of theories and techniques to generate a "custom built" (i.e., wake adapted) propeller for the ship under consideration, their expertise is usually not required in the early stages of preliminary design simply because the design has not been refined enough beyond gross estimates. At this stage, the designer strives to formulate what is possible based on previous experience. For preliminary power estimation, previous propeller designs (i.e., "stock" propellers) and results from methodical series of model propellers are analyzed by the designer in order to select the "best" available propeller under various conditions posed by the problem under consideration. Three examples of typical problems encountered in preliminary ship design are:

1) Given the ship's effective horsepower at a specific speed and estimates of hull performance parameters, which propeller, as determined by certain principal characteristics, will require the least amount of delivered power from the propulsion plant?

2) Given the delivered power from a specific propulsion system in terms of torque and revolution rate at the propeller/shaft interface and estimates of hull performance parameters, which propeller will generate the largest effective horsepower and speed parameters?

3) Given a ship's effective horsepower and speed, various hull performance parameters, and the propulsion plant's delivered power characteristics, which propeller will "match"

these requirements at a minimum amount of weight for a specified material?

(Author's Note: For the sake of brevity, the three selection problems just cited will, henceforth, be referred to as "Design Case No. 1", "Design Case No. 2" and "Design Case No. 3", respectively.)

For this study, the methodical propeller series method is viewed as the designer's choice for preliminary powering analysis. One of the most-widely used methodical series data on model propellers is the Wageningen B-Screw Series. Initially, the results of the series were presented as tabulations of non-dimensional thrust and torque coefficients (K_T and K_Q respectively) versus the non-dimensional advance ratio (J) for analytical work and as the familiar "Bp-δ" and "Bu-δ" diagrams for design purposes. As "trial & error" design methods performed by hand in all engineering disciplines gradually transcended to numerical manipulation by the modern digital computer, the necessity for the adaption of the Series results to a format suitable for use in computer-aided design methods became obvious. This was accomplished through multiple regression analysis of the original open-water test data of the 120 propeller models in the Series and presented in the form of polynomial expressions for "K_T" and "K_Q" [Refs. 1,2].

The adaptation of the Wageningen B-Screw Series polynomials to various types of propeller selection problems formulated

for computer solution has been implemented recently by two authors. Triantafyllou [Ref. 3] and, of late, Markussen [Ref. 4] presented different propeller selection problems and proposed different schemes for computer-aided "optimized" solutions. In short, specific expressions for the constraints imposed and the objective (optimality condition) to be maximized, expressed in terms of a number of design variables and parameters, were developed. Then, each system of equations was solved by a Newton-Raphson method to give a solution set of the design variables which maximized the objective and met all constraints.

Rather than formulating and coding a different optimization scheme each time a propeller selection problem presents a different combination and number of design parameters, variables and constraints, a better approach would involve formulating the problem (constraints and objective function) once in terms of all design parameters and variables and utilizing a general purpose optimization scheme which can handle any combination and number of constraints and design variables. This alternative certainly allows the designer more flexibility in solving his problem. Moreover, it eliminates repetitive coding and debugging associated with the implementation of a computer-sided solution for each particular design problem.

B. PROBLEM STATEMENT

The problem, then, is that the previously cited computer-aided "optimized" solutions to the propeller selection problem are not broad enough in capability to handle variations in the problem formulation. The objective of this thesis is to apply an available general purpose optimization computer code to the solution of various propeller selection problems encountered in Preliminary Ship Design in order to enhance the flexibility of the selection procedure.

C. SCOPE

To achieve the stated objective, the general purpose non-linear optimization code CONMIN [Refs. 5,6] together with the engineering synthesis code COPES [Ref. 7] (hereafter referred to as collectively as COPES/CONMIN) is utilized in the solution of the three previously cited preliminary design propeller selection problems. Using the Wageningen B-Screw Series propeller characteristics expressed in polynomial expressions of various design variables, three "analysis" codes, required by COPES/CONMIN, are developed in such a way that various combinations of design variables and constraints are used, thereby demonstrating the applicability of the COPES/CONMIN optimization program in the solution of propeller selection problems.

D. THESIS ORGANIZATION

The remainder of the thesis is organized in the following manner.

Chapter II presents a short description of the optimization problem in general terms and a follow-on discussion of the COPES/CONMIN optimization program and the mathematical techniques employed therein.

Chapter III introduces definitions and concepts applicable to the propeller selection problem. A subsequent discussion on the Wageningen B-Screw Series is followed by final comments on constraints imposed on the propeller selection problem.

Chapter IV presents the formulation of the propeller selection problem as a design optimization problem which can be solved using COPES/CONMIN.

Chapter V discusses the background, formulation and programming utilized in estimating a propeller blade's weight for subsequent consideration as an objective function.

Chapter VI reviews the author's modifications to the propeller strength analysis developed by Schoenherr [Ref. 8] in the early 1960's for the American Bureau of Shipping. A subsequent discussion on the programming details of FORTRAN codes, which are utilized for the determination of adequate propeller blade strength, completes the chapter.

Chapter VII reviews the formulation and programming for the analysis code which is used in solving propeller selection problems represented by Design Case No. 1. Sample solutions are presented and compared to those presented previously by other authors.

Chapters VIII and IX consider Design Case No. 2 and Design Case No. 3 selection problems, respectively, in a similar fashion to Chapter VII.

Chapter X, the final chapter, presents the author's conclusions and recommendations.

As a final note, all computer coding presented in this thesis is done in FORTRAN IV, the language used by COPES/CONMIN. For the reader's convenience, Appendix A provides a cross-reference of the symbols presented throughout the thesis to appropriate FORTRAN variable names appearing in the author's codes.

II. OPTIMIZATION

A. INTRODUCTION

The purpose of this chapter is to introduce definitions and concepts used in the formulation and solution of the general optimization problem. Then, a short discussion on the theory and implementation details of COPES/CONMIN is presented.

For further study on the theory and methods of optimization, the reader is directed to the texts by Fox [Ref. 9], Fiacco and McCormick [Ref. 10], and Himmelblau [Ref. 11].

B. DEFINITIONS

Before discussing the techniques of optimization and their application to engineering problems, some preliminary definitions of basic terminology should be stated. Terms which have relevant significance are:

1) Parameters--The numerical quantities for which values are assigned to produce a design are called parameters. From this, it follows that a design may be specified by a vector D containing "p" components, each of which is associated with a parameter. That is:

$$\overline{D} = \begin{Bmatrix} D_1 \\ \cdot \\ \cdot \\ \cdot \\ D_p \end{Bmatrix} \qquad (2.1)$$

However, in a design process, the parameters are determined by some logical procedure through analysis of some kind. Some might take on fixed values to become "preassigned" parameters. Interrelationships among other parameters might exist so that only some of the parameters are changed when one design is compared to another. This consequence leads to the definition of "design variable".

2) Design Variables--The parameters for which values are chosen in some fashion to produce a design are called design variables. They represent an ordered collection of components which is a subset of the design vector $\bar{D}$. This subset is unique in that its components are "variable", i.e., they may take on different values in the design process. Having "preassigned" or fixed some of the design's parameters and only allowing the remaining "design variables" to change, leads to the conclusion that a design is now uniquely specified by a vector $\bar{X}$ containing "n" components ($n \leq p$), each of which is associated with a design variable. That is:

$$\bar{X} = \begin{Bmatrix} x_1 \\ \vdots \\ x_n \end{Bmatrix} \tag{2.2}$$

3) Objective Function--The computable function of all or some of the design's preassigned parameters and/or design variables, with respect to which the design is to be optimized, is called the objective function. Single valued in

quantitative terms, the objective function's minimum or maximum value represents the "best" obtainable or "optimized" design. It is expressed as $F(\bar{D})$ to show its dependence on the design's parameters. But, since a design can be uniquely defined by $\bar{X}$ alone, then clearly $F(\bar{X})$ suffices as an expression for the objective function.

4) Constraints--Restrictions on the design which must be satisfied in order to produce an acceptable design are called constraints. A constraint may be classified as a "side" or a "behavior" constraint. A side constraint restricts or bounds the range of the design for reasons other than direct consideration of performance. The side constraint on the "i"th design variable may be expressed as:

$$X_i^{lower} \leq X_i \leq X_i^{upper} \qquad i = 1,\ldots,n \qquad (2.3)$$

A constraint derived from those performance or behavior requirements that are explicitly considered is called a behavior constraint. Most often, it appears as a computable functional relation involving the design's parameters, both preassigned and variable alike. The relation may be an inequality so that the "j"th of "m" inequality constraints can be expressed as:

$$G_j(\bar{D}) \leq 0 \qquad j = 1,\ldots,m \qquad (2.4)$$

Alternatively, the relation may be an equality on the "k"th of "ℓ" equality constraints expressed as:

$$H_k(\overline{D}) = 0 \qquad k = 1,\ldots,\ell \tag{2.5}$$

Of noteworthy importance here is that, as before, if some of the design's parameters are preassigned, then the resulting design is that defined by $\overline{X}$ which contains only the parameters that can be varied in the design process, i.e., the design variables. Therefore, constraints imposed upon the design may be expressed under one equation as:

$$\begin{aligned} G_j(\overline{X}) &\leq 0 && j = 1,\ldots,m \\ H_k(\overline{X}) &= 0 && k = 1,\ldots,\ell \\ X_i^{lower} \leq X_i &\leq X_i^{upper} && i = 1,\ldots,n \end{aligned} \tag{2.6}$$

A final form for constraints is that of the discrete-valued design variable.

5) Feasible Design--A design in which specified constraints are satisfied is called a feasible or "acceptable" design.

6) Infeasible Design--A design in which constraints are violated is called an infeasible or "unacceptable" design.

C. PROBLEM STATEMENT

If one presupposes that a range of designs exists within a selected design concept, then it follows that different

methodologies also exist by which one may choose the parameters which describe the design. One such method is optimization where parameters are chosen in a way that the design will satisfy all of the limitations and restrictions imposed upon it and will be "best" in some sense. In view of the foregoing definitions, optimization is then a selection method applied to a design problem by which an objective function $F(\bar{D})$ is minimized to produce an acceptable design which satisfies a certain set of requirements called constraints.

Formulated mathematically, the general, non-linear, constrained optimization problem may be stated under one equation as:

$$
\begin{array}{llll}
\text{Minimize:} & F(\bar{D}) = OBJ & & \\
\text{Subject to:} & G_j(\bar{D}) \leq 0 & j = 1,\ldots,m & (2.7) \\
 & H_k(\bar{D}) \leq 0 & k = 1,\ldots,\ell & \\
 & X_i^{lower} \leq X_i \leq X_i^{upper} & i = 1,\ldots,n &
\end{array}
$$

Again, as pointed out in the previous section, the design may be uniquely defined by just its design variables as specified by $\bar{X}$ when some parameters are preassigned. Thus, the general, non-linear, constrained optimization problem can now be stated under one equation as:

$$
\begin{aligned}
&\text{Minimize:} && F(\overline{X}) = OBJ && \\
&\text{Subject to:} && G(\overline{X}) \leq 0 && j = 1,\ldots,m \qquad (2.8) \\
& && H_k(\overline{X}) = 0 && k = 1,\ldots,\ell \\
& && X_i^{lower} \leq X_i \leq X_i^{upper} && i = 1,\ldots,n
\end{aligned}
$$

Solutions methods for this optimization problem are abundant. Those pertaining to the linear and quadratic optimization problems involving a few design variables are most often presented in graphical or analytic form, although numerical schemes are, by no means, a dormant form. Structural and thermal problem solutions are most prevalent. However, as the optimization problem becomes more complex in terms of non-linear relationships among an increasing number of design variables and of an increased number of design constraints, numerical or mathematical programming techniques dominate the solution methods.

To limit the scope of this discussion, only the numerical techniques relevant to COPES/CONMIN will be considered. For more background on optimization techniques and applications, the reader is directed to a recent paper by Vanderplaats [Ref. 12] which presents a concise, but thorough, qualitative review of optimization. Although this paper deals exclusively with the application of design optimization to structural problems, it also contains a very extensive and current list of references on general techniques and applications of optimization.

D. COPES/CONMIN

As previously stated in Chapter I, COPES/CONMIN is the collective acronym for the FORTRAN program utilizing the optimization code CONMIN and the synthesis code COPES. COPES stands for COntrol Program for Engineering Synthesis; CONMIN is an acronym for CONstrained function MINimization.

1. CONMIN

CONMIN is a FORTRAN program, in subroutine form, which solves the general non-linear constrained optimization problem as stated:

$$\text{Minimize:} \quad F(\overline{X}) = \text{OBJ}$$

$$\text{Subject to:} \quad G_j(\overline{X}) \leq 0 \qquad j = 1,\ldots,m \qquad (2.9)$$

$$X_i^{lower} \leq X_i \leq X_i^{upper} \qquad i = 1,\ldots,n$$

Equation (2.9) applies to the entire statement. Observe that equation (2.9) differs from equation (2.8) in that the equality constraint set, given by $H_k(\overline{X}) = 0$, is not specified. This is because the version of COPES/CONMIN used in this study does not consider these types of constraints. However, this will not pose any difficulty in solving the propeller selection problems previously cited.

Again, $F(\overline{X})$ is the objective function (OBJ). The vector $\overline{X}$ contains the "n" design variables (NDV). $G_j(\overline{X})$ are the "m" inequality behavior constraints (NCON) imposed on the optimization problem; X_i^{lower} and X_i^{upper} are the

respective lower and upper side constraints which bound the "design space" over which $F(\overline{X})$ and $G_j(\overline{X})$ are defined. As functional relationships involving $\overline{X}$, $F(\overline{X})$ and $G_j(\overline{X})$ may be implicit or explicit, but, in any event, must be continuous and have finite numerical values.

When the inequality condition of equation (2.9) is not satisfied, i.e., $G_j(\overline{X}) > 0$ for any constraint, the constraint is said to be violated. If the equality condition is met, i.e., $G_j(\overline{X}) = 0$ for any constraint, the constraint is said to be active. And, finally, if the inequality condition is satisfied, i.e., $G_j(\overline{X}) < 0$, for any constraint, that constraint is termed inactive. Any design, defined by $\overline{X}$, which satisfies the inequalities of equation (2.9) is designated as a feasible design. Likewise, any one which violates these inequalities is termed an infeasible design. The feasible design with the minimum objective function value, often referred to as the "minimum feasible design", will, therefore, be the optimum design.

During the optimization process, CONMIN employs the Fletcher-Reeves algorithm [Ref. 13] for locally unconstrained problems, and Zoutendijk's method of deasible directions [Refs. 14,15] for locally constrained problems, in a numerical procedure which attempts to minimize the objective function, $F(\overline{X}) = OBJ$, until one or more of the constraints, $G_j(\overline{X})$, becomes active. The numerical search procedure begins with an initial $\overline{X}$ vector which may or may not specify a feasible

design. Modifications are included in CONMIN so that, if the initial design is infeasible, a feasible solution will be obtained with minimal increase in $F(\bar{X})$. By iteratively updating the design vector $\bar{X}$ by the following relation:

$$\bar{X}^{(q+1)} = \bar{X}^{(q)} + \alpha^* \bar{S}^{(q)} \tag{2.10}$$

the optimization process continues by following the constraint boundaries in a direction of search $\bar{S}$ so that the value of $F(\bar{X})$ decreases with each iteration q. The scalar α^* defines the distance of travel in the direction of search $\bar{S}$. The process terminates when a vector $\bar{X}$ is found such that no further decrease in $F(\bar{X})$ can be made. The vector $\bar{X}$ is considered to be optimal and, at least, a local minimum.

CONMIN can be used alone as a subroutine in any FORTRAN program where numerical optimization is desired. However, in order to make the optimization process more "user-friendly", CONMIN has been coupled to COPES in order to simplify its application to various types of problems. Further information on CONMIN can be found in previously cited references [5] and [6].

2. <u>COPES</u>

COPES is a FORTRAN program that provides automated design and trade-off capability to the design engineer. It utilizes the optimizer CONMIN to provide the following six specific capabilities:

1) simple analysis

2) optimization

3) sensitivity analysis

4) two variable function space analysis

5) optimum sensitivity

6) optimization using approximation techniques

During the execution of COPES, say for optimization, three principal tasks are performed:

1) data management on the design variables and constraints through location assignments in a FORTRAN common block called GLOBCM.

2) decision process control on the attainment of an optimal design vector $\overline{X}$ through multiple calls to the optimizer until a minimum or maximum value of OBJ is achieved and all $G_j(\overline{X})$ are satisfied.

3) evaluation of OBJ and $G_j(\overline{X})$ at each $\overline{X}^q$ and $\overline{X}^{q+1}$ when ICALC = 2 through multiple calls to the user-provided analysis subprogram, SUBROUTINE ANALIZ.

For the application under consideration in this study, only the optimization capability will be used. Therefore, further elaboration on the other capabilities is not warranted.

Reference [7] is the user's manual for COPES/CONMIN. Details on the mechanics of user implementation are presented with subsequent illustration by example. The reader is, therefore, encouraged to familiarize himself with the reference. However, at this point, it is sufficient to be aware of the fact that a user of COPES/CONMIN is required to:

1) provide a FORTRAN subroutine called ANALIZ which performs the input of preassigned parameters, the evaluation of the objective function and constraints during the analysis phase of the optimization search and the output of the results.

2) provide an assembled deck of control cards required by COPES.

E. CONCLUDING NOTE

The field of optimization is both extensive and complex and, therefore, the foregoing presentation is, by no means, complete in every detail. However, it is felt that the preceding overview, in conjunction with the cited references, covers the necessary prerequisites that will enable the reader to follow the application of COPES/CONMIN to the various propeller selection problems in the chapters that follow.

III. POWERING, PERFORMANCE AND PROPELLERS

A. INTRODUCTION

The purpose of this chapter is to present an overview of the terminology and concepts that pertain to ship propulsion, propeller selection and the use of model propeller test data. Initially, fundamental definitions used in ship powering problems are presented. This is followed by a discussion of the "classic" types of propeller design/selection problems encountered by the naval architect and marine and naval engineers. Propeller model testing and propeller performance characteristics are reviewed next. The chapter is completed with a discussion of the Wageningen B-Screw Series.

The goal here is brevity. The reader is, therefore, encouraged to investigate the references cited for further details.

B. DEFINITIONS

Some fundamental terms associated with most propeller design/selection problems are:

1) Effective Horsepower (P_E)--power required to tow the "bare" hull (without propeller; rudder and appendage allowance assumed included) that generates a given resistance (R_T) at a given speed (V). It is determined by:

$$P_E = \frac{R_T V}{550} \qquad (3.1)$$

2) Thrust Horsepower (P_T)--power delivered to water by a propeller developing a thrust force (T) and moving at a speed of advance (V_A) without the influence of a hull form ahead of it. P_T is determined by:

$$P_T = \frac{T\ V_A}{550} \tag{3.2}$$

3) Delivered Horsepower (P_D)--power delivered by shaft to propeller, normally specified at the outboard side of the stern tube. Q_S is the torque delivered to the propeller; n_P is the revolution rate of the shaft and, consequently, the propeller. P_D is determined by:

$$P_D = \frac{2\pi\ Q_S\ n_P}{550} \tag{3.3}$$

4) Shaft Horsepower (P_S)--power delivered to the inboard side of the stern tube having a transmission efficiency of η_S. P_S is determined by

$$P_S = \frac{P_D}{\eta_S} \tag{3.4}$$

5) Brake Horsepower (P_B)--power delivered by the prime mover at connection flange to the power train. While P_B is normally associated with the prime mover's rated power at this connection (BHP), it can also be specified from the power train/propeller side as:

$$P_B = \frac{P_S}{\eta_B \, \eta_G} \tag{3.5}$$

where η_B and η_G are, respectively, the bearing system and reduction gear transmission efficiencies.

6) Thrust deduction factor (1-td)--ratio of the tow resistance (R_T) to the thrust (T) provided by the propeller. It is determined by

$$(1-td) = \frac{R_T}{T} \tag{3.6}$$

7) Wake Factor (Taylor's) (1-wt)--ratio of the speed of advance (V_A) to the ship's speed (V). It is given by:

$$(1-wt) = \frac{V_A}{V} \tag{3.7}$$

8) Advance Ratio (J)--a non-dimensional value, associated with propeller test data presentation (see figure (3.1), given by the following relation:

$$J = \frac{V(1-wt)}{n_P \, D} = \frac{V_A}{n_P \, D} \tag{3.8}$$

9) Thrust Coefficient (K_T)--a non-dimensional value associated with the thrust force (T) developed by a propeller of diameter D which is turning at a rate n_P and operating in a fluid of density ρ. It is defined by the following expression:

$$K_T = \frac{T}{\rho\, n_P^2\, D^4} \tag{3.9}$$

10) Torque Coefficient (K_Q)--a non-dimensional value associated with the torque (Q_P) absorbed by a propeller of diameter D which is turning at a rate n_P and operating in a fluid of density ρ. It is defined by the following expression:

$$K_Q = \frac{Q_P}{\rho\, n_P^2\, D^5} \tag{3.10}$$

11) Open Water Efficiency (η_o)--the ratio of P_T to P_D for a propeller in open water conditions, with a uniform inflow velocity field at a speed of advance V_A. It is expressed as:

$$\eta_o = \frac{P_T}{P_D} = \frac{T\, V_A}{2\pi\, n_P\, Q_S} = \frac{J\, K_T}{2\pi\, K_Q} \tag{3.11}$$

12) Hull Efficiency (η_H)--a ratio of work done on the ship to that done by the propeller expressed as:

$$\eta_H = \frac{P_E}{P_T} = \frac{R_T\, V}{T\, V_A} = \frac{(1\text{-td})}{(1\text{-wt})} \tag{3.12}$$

13) Relative Rotative Efficiency (η_R)--the ratio of the actual, behind-hull efficiency to the open water efficiency. The value of η_R does not, in general, depart from the value

of 1.0. Most often, η_R varies between 0.95 and 1.0 for twin-screw ships and between 1.0 and 1.1 for single screw ships.

Applicable units for the terms in the expressions above are:

1) horsepower (hp)--P_E, P_T, P_S, P_D and P_B
2) pounds (lbf)--R_T, T
3) feet/second (ft/sec)--V, V_A
4) foot-pounds (ft-lbf)--Q_S, Q_P
5) feet (ft)--D
6) revolutions/second (rps)--n_P
7) revolutions/minute (rpm)--$N_P = n_P/60.0$

The quantities T, V_A, D, Q_P and n_P are obtained from the propeller test data results. The quantities R_T and V are specified from the design point on the R-V curve for the hull under study. The quantity ρ is a property of the fluid in which the hull and propeller operate. And, finally, η_B, η_G and η_S are characteristics of the bearing, gear and stern tube systems. In preliminary design studies, nominal values, based on previous designs, are usually assumed unless, of course, these systems have been selected and actual values can be specified.

C. POWERING CONCEPTS

1. Basic Relations

Simply stated, the fundamental powering relationship to be solved in ship propulsion and powering problems is:

$$P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \, \eta_o \, P_D \tag{3.13}$$

Utilizing the definitions just presented, equation (3.13) can be rewritten as:

$$\frac{R_T \, V}{550} = \frac{(1-td)}{(1-wt)} \cdot \eta_R \, \eta_o \cdot \frac{2\pi \, Q_S \, n_P}{550} \tag{3.14}$$

Rearranging terms of equation (3.14) gives:

$$\frac{R_T}{(1-td)} \cdot \frac{(1-wt)V}{550} = \eta_R \, \eta_o \cdot \frac{2\pi \, Q_S \, n_P}{550} \tag{3.15}$$

And, finally, when substitutions are made, equation (3.15) becomes:

$$\frac{T \, V_A}{550} = \frac{T(1-wt)V}{550} = \eta_R \, \eta_o \cdot \frac{2\pi \, Q_S \, n_P}{550} \tag{3.16}$$

Equations (3.14), (3.15), and (3.16) provide the basis for different approaches to the solution of a typical powering problem. More background and information on the definitions and equations presented above may be found in Chapter VI, Sections 10-16 in the text by Comstock [Ref. 16] and O'Brien's book [Ref. 17].

2. Approaches to the Powering Problem

From equation (3.16), three types of propeller selection problems are discernible. In the first instance, the propeller thrust T and the propeller's speed of advance V_A

are taken as known quantities. The fact that T is known substantiates the "Thrust Approach" nomenclature given to this type of selection problem. In the preliminary (or, in some circles, conceptual) ship design phase, the specification of T is based upon the requirement imposed by the resistance of the ship (R_T) at its design speed (V) (or, the effective horsepower (P_E) at V) and estimates of wt and td in the absence of wake surveys and self-propulsion data from model tests. Essentially, the thrust delivered by a selected propeller must provide, at least, the thrust required for the ship hull under study. The objective in the "Thrust Approach" selection problem is to determine, by logical means, the appropriate values of Q_S and n_P when the open water efficiency (η_o) is set by the selected propeller and its performance characteristics.

In the second instance, the delivered torque (Q_S) and the propeller shaft speed (n_P) are taken to be known. The "Power Approach" nomenclature is given to propeller selection problems of this type because P_D is known. Here, with the shaft and propeller speeds being equal, the torque absorbed by the propeller (Q_P) must be, at least, equivalent to the delivered torque (Q_S). The corresponding objective in the "Power Approach" selection problem is to determine, by logical means, the expected ship speed (V) (or, the speed of advance (V_A)) and the associated thrust (T) that can be developed when the open water efficiency (η_o) is, again, set by the selected propeller and its performance characteristics.

The final, and most familiar, types of propeller selection problem occurs when T, V_A or V, Q_S and n_P are all known. From equation (3.16), the open water efficiency (η_o) is now established as a requirement to be met. The objective is, simply, to select a propeller whose open water efficiency (η_o), developed thrust and absorbed torque are equivalent to or "match" the requirements imposed. Obviously, this approach on the selection problem has been designated as a "matching problem".

The reader is directed to the paper by Vassilopoulos [Ref. 18] for further information.

D. PROPELLER PERFORMANCE CHARACTERISTICS

Up until the late 1950's, much of the knowledge about the performance of propellers has been gained from experience with models. To study the relationships governing their behavior, a model propeller is built and run in a towing tank without any hull ahead of it. This is done by running the propeller on a long shaft projecting well ahead of a narrow, hydrodynamically shaped pod or "propeller boat" which contains the driving mechanism and recording apparatus and is attached to the towing carriage. The propeller advances into undisturbed fluid (usually water of density ρ and kinematic viscosity ν) so that the speed of advance (V_A) is known and the flow into the "disc" swept by the turning blades is uniform. For the model propeller of diameter (D) under test, readings of thrust (T), torque (Q_S) and shaft revolutions (n_P)

are recorded over a range of values for speed of advance (V_A) in this "open water" condition.

Using the laws of similitude, the collected data is reduced and scaled appropriately into the familiar functional relationships between the advance ratio (J) and the non-dimensional coefficients of propeller performance. These coefficients or performance characteristics, defined previously, are:

1) Thrust Coefficient (K_T)
2) Torque Coefficient (K_Q)
3) Open Water Efficiency (η_o)

Figure (3.1) graphically depicts the relationship between J and K_T and K_Q derived from test data for a propeller defined by a specific expanded area ratio (A_E/A_O), pitch-diameter ratio (P/D), number of blades (Z) and thickness-to-chord ratio (t/c).

Definitions of these terms with graphical illustrations pertaining to various aspects of propeller geometry can be found in Section 15 of references [16], [17] and in van Manen's publication [Ref. 19].

More recently, highly analytical theories (lifting line, modified lifting line, lifting surface, etc.) for use with high-speed digital computers have been formulated and subsequently used in "modeling", in a mathematical sense, the propeller and its behavior in the "wake adapted" (or, behind hull) condition as well as the "open water" condition.

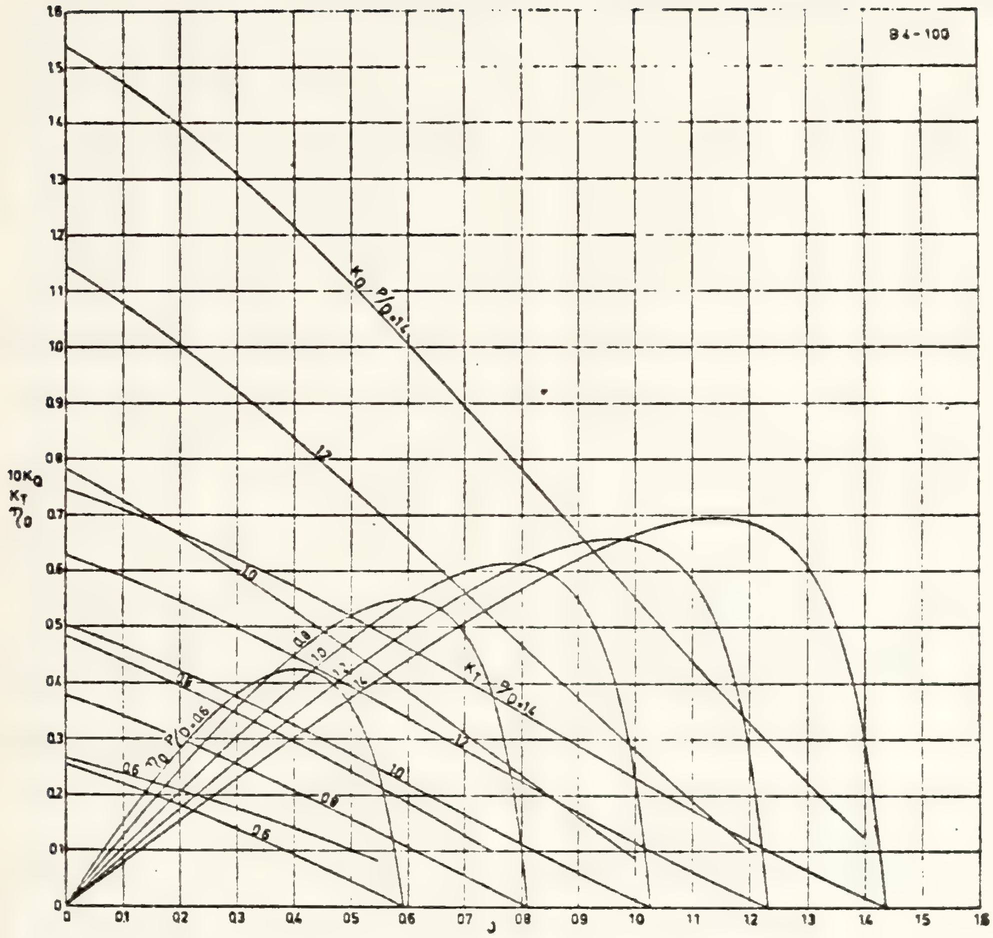

Figure 3.1 Open Water Test Results--B 4-100 Series Propeller

Additional benefits derived from this approach to propeller performance analysis include:

1) determination of blade section profiles along the propeller's blade radius (R) to achieve uniform lift and internal stress distributions;

2) computation of "off-design" performance characteristics in all quadrants;

3) subsequent determination of hull surface forces, bearing loads and spindle torques induced by the propeller;

4) prediction of steady and unsteady stress distributions in the propeller blade using the finite element method on the blade of the propeller under study.

Obviously, this approach to propeller performance analysis serves to:

1) eliminate the time-consuming and expensive model construction and testing of propellers in tow tanks and cavitation tunnels;

2) eliminate the "scaling" discrepancies which inhibit the reliability of design charts and model propeller data;

3) eliminate those design charts altogether.

As in the case with model experiments, however, the ultimate objective remains the same, i.e., establishing the performance characteristics of the propeller in terms of K_T, K_Q and as functions of J. Having these relationships enables the ship designer to proceed in solving the power equation (equation (3.13)) through any of the approaches previously discussed.

E. THE WAGENINGEN B-SCREW SERIES

1. Background

The model test data of the Wageningen B-Screw Series have been selected for use in the powering problems to be solved utilizing COPES/CONMIN. The choice was driven by the following considerations:

1) the Series is widely known and, despite its growing obsolescence, is still used in preliminary ship design studies.

2) the availability of previous investigations [Refs. 3,4] which utilized the series, for comparative analysis of optimization results.

3) the applicability of the polynomial expressions for K_T and K_Q to computer-aided analysis.

The Series tests were conducted from 1940 through 1960 and, therefore, represent propeller designs (principally naval and merchant applications) and design philosophy of that era.

Specifically, the Series consists of 120 model propellers. As is customary in methodical or systematic model propeller series testing, the number of blades (Z), expanded area ratio (A_E/A_O) and pitch-diameter ratio (P/D) are varied systematically, while the blade outline, the profile of the blade's cross section along the blade radius, blade cross section maximum thickness (t), blade section chord length (c), diameter (D) and propeller hub-to-diameter ratio (d/D) were kept constant for given values of A_E/A_O and Z.

Table (I) summarizes the variations in Z and A_E/A_O for each set of model propellers having pitch-diameter ratios (P/D) of 0.4, 0.6, 0.8, 1.0, 1.2 and 1.4.

TABLE I

Summary of the Wageningen B-Screw Series

Blade number Z	Blade area ratio A_E/A_o															
2	0.30															
3		0.35			0.50			0.65			0.80					
4			0.40			0.55			0.70			0.85			1.00	
5				0.45			0.60			0.75						1.05
6					0.50			0.65			0.80					
7						0.55			0.70			0.85				

2. Series Results

The test results of the Wageningen B-Screw Series were originally presented in the form of Bp-δ, Bu-δ and K_T, K_Q, and -J diagrams. As stated in Chapter I, multiple regression analysis was performaed (again, [Refs. 1,2]) on the results to produce the polynomial expressions for K_T and K_Q. The open water efficiency (η_o), as a function of J, follows from equation (3.11). The correction for "scale effects" was achieved by using Lerb's method of equivalent profiles [Ref. 20]. Although Triantafyllou's thesis [Ref. 21] suggests an improved method for scale correction, the results of Reference [2] will be used in this study.

In propeller selection problems which use this Series, values for K_T and K_Q are defined as:

$$K_T = f_1(J, P/D, A_E/A_O, Z, t^*/c_{.75R})$$
$$K_Q = f_2(J, P/D, A_E/A_O, Z, t^*/c_{.75R}) \qquad (3.17)$$

To compute K_T and K_Q, the following equations are used:

$$K_T = K'_T + \Delta K_T$$
$$K_Q = K'_Q + \Delta K_Q \qquad (3.18)$$

The polynomial expressions found in Tables (5) and (6) of Reference [2] are then used to evaluate to components K'_T, K'_Q, ΔK_T and ΔK_Q.

Table (5) in Reference [2] lists the coefficients used in the polynomial expressions for K'_T and K'_Q at an equivalent Reynolds number ($Rn_{.75R}$) of 2×10^6. It is defined as:

$$Rn_{.75R} = \frac{c_{.75R}\sqrt{(V_A)^2 + (0.75\pi n_P D^2)}}{\nu} \qquad (3.19)$$

where:

ν = kinematic viscosity of the fluid (ft^2/sec);

$c_{.75R}$ = blade section chord length at 3/4 propeller radius (.75R) in feet (ft).

To account for "other effects", coefficients ΔK_T and ΔK_Q are introduced. Table (6) in Reference [2] lists the coefficients used in the polynomial expressions for these coefficients. "Other effects" include the operation of the propeller at an equivalent Reynolds Number different from 2×10^6. Also, variations in other parameters which define the propeller's geometry, specifically t/c values different from the ones fixed by the Wageningen propellers, are taken into account by corrections to the equivalent Reynolds number. By keeping the blade section's chord length (c) at the value of the Wageningen propeller, a change in a blade section's maximum thickness from the standard one defined by the Series (t) to one preferred in the selection (t^*) produces a new equivalent Reynolds number ($Rn^*_{.75R}$) given by:

$$Rn^*_{.75R} = \exp\left[4.6052 + \left\{\sqrt{\frac{1+2(t/c_{.75R})}{1+2(t^*/c_{.75R})}}\,(\ln Rn_{.75R} - 4.6052)\right\}\right] \tag{3.20}$$

where:

$Rn^*_{.75R}$ = the new equivalent Reynolds number;

$(t^*/c)_{.75R}$ = new equivalent t/c at 3/4 propeller radius;

$Rn_{.75R}$ = the Reynolds number computed by equation (3.19);

$(t/c)_{.75R}$ = standard equivalent t/c at 3/4 propeller radius for Wageningen propellers.

For the Wageningen B-Screw Series, the standard equivalent t/c is given by:

$$t/c_{.75R} = \frac{(0.0185 - 0.00125Z)Z}{2.073\ A_E/A_O} \qquad (3.21)$$

Further details on blade section geometry will be addressed in Chapter V. Reference [2] contains background and other information on the equations above.

3. Limitations on Series Data

In utilizing the Wageningen B-Screw Series in any propeller selection problem, the following restrictions apply to the Series data:

1) Number of Propeller Blades (Z)--The Series considers only propellers with numbers of blades as shown in Table (I). Therefore,

$$Z = 2,\ 3,\ 4,\ 5,\ 6 \text{ or } 7 \qquad (3.22)$$

However, the two bladed propeller, i.e., Z = 2, is not very common in conventional merchant and naval ship designs and, therefore, is not included in this study.

2) Equivalent Reynolds Number--The Series data, as published, is valid only in the range of equivalent Reynolds numbers given by:

$$2 \times 10^6 \leq Rn_{.75R} \leq 2 \times 10^9 \qquad (3.23)$$

If the equivalent t/c is varied from the standard equivalent value $(t/c)_{.75R}$, then the new equivalent Reynolds number $(Rn^*_{.75R})$, which results from this variation, must lie within the same limits. That is,

$$2 \times 10^6 \le Rn^*_{.75R} \le 2 \times 10^9 \qquad (3.24)$$

These limits are appropriate for full-size propellers. For example, given the following:

a) wt = .22

b) V = 20 (knots)

c) N_p = 104 (rpms)

d) D = 25 (ft)

e) $c_{.75R}$ = 4.0 (ft)

f) $\nu = 1.2285 \times 10$ (ft^2/sec)

the value for $Rn_{.75R}$ is equal to 3.619×10^7.

3) Pitch-diameter Ratio (P/D)--The series data considers only pitch diameter ratios in the range given by:

$$0.4 \le P/D \le 1.4 \qquad (3.25)$$

4) Advance Ratio (J)--An inspection of the Series results in graphical format shows that J varies over a range given by:

$$0 < J \le 1.6 \qquad (3.26)$$

5) Expanded Area Ratio (A_E/A_O)--Using Table (I), A_E/A_O varies over certain ranges depending on Z. This is stated as:

$$0.35 \leq A_E/A_O \leq 0.8 \qquad Z = 3 \qquad (3.27)$$

$$0.40 \leq A_E/A_O \leq 1.0 \qquad Z = 4 \qquad (3.28)$$

$$0.45 \leq A_E/A_O \leq 1.05 \qquad Z = 5 \qquad (3.29)$$

$$0.50 \leq A_E/A_O \leq 0.8 \qquad Z = 6 \qquad (3.30)$$

$$0.55 \leq A_E/A_O \leq 0.85 \qquad Z = 7 \qquad (3.31)$$

6) Hub diameter-to-Propeller Diameter Ratio (d/D)--From Table 37, Section 17 of Reference [16], the Series data requires that:

$$d/D = 0.18 \qquad Z = 3,7 \qquad (3.32)$$

$$d/D \doteq 0.167 \qquad Z = 4,5,6 \qquad (3.33)$$

F. SUMMARY

From the preceding discussions, the following observations can be made:

1) the "Design Cases", defined in Chapter I, are examples of the powering equation solution approaches. That is, Design

Case No. 1 constitutes a "Thrust Approach" problem; Design Case No. 2, a "Power Approach" one; Design Case No. 3, a "Matching" problem.

2) equations (3.17) and (3.8) imply that an optimization solution to the "Design Cases" will involve P_E, V, wt, D, P/D, A_E/A_O, $(t^*/c)_{.75R}$, Q_S and n_P as possible design variables.

3) when viewed from the concepts on optimization presented in Chapter II, equations (3.25) through (3.31) constitute side constraints to an optimized solution of a propeller selection problem which uses the Wageningen B-Screw Series. Having noted these points, the propeller selection problem can now be formulated as a general, non-linear, constrained optimization problem.

IV. PROPELLER SELECTION--AN OPTIMIZATION PROBLEM

A. INTRODUCTION

The purpose of this chapter is to present the formulation of the propeller selection problem as an optimization problem that can be solved using COPES/CONMIN. Three usual restrictions considered by the designer in any propeller selection analysis are stated as constraints. Then, the components of $\overline{D}$ and $\overline{X}$ are assembled based on requirements from previously cited relationships. The restrictions considered by the designer and the limitations imposed by the use of the Wageningen B-Screw Series are presented in inequality constraint format. A formal statement of the propeller selection problem as an optimization problem is followed by a review of the GLOBCM common block format and the basic subprograms used in all three versions of SUBROUTINE ANALIZ that pertain to each Design Case.

The FORTRAN subprogram listings are found in Appendix B. Comment cards have been used extensively in the coding development to assist the reader.

B. DESIGNER'S CONSIDERATIONS

1. Propeller Size

The first restriction on the selection of any propeller is size. That is, the propeller race in the stern of the hull under consideration will only accommodate a

propeller of some given maximum diameter (D_{lim}). As a constraint on a selected propeller of diameter D, this may be written as:

$$D \leq D_{lim} \qquad (4.1)$$

or, alternatively, as:

$$G_9(\bar{X}) = \frac{D}{D_{lim}} - 1 \leq 0 \qquad (4.2)$$

2. <u>Cavitation</u>

Another item of importance in propeller selection is the cavitation phenomenon. When a propeller of given diameter D and expanded area ratio A_E/A_O is operating to produce a thrust T, the formation and subsequent collapse of water vapor bubbles on the blade surface, i.e., cavitation, is likely to occur if the localized surface pressures, usually on the "back" side of the blade, drop below the pressure at which the fluid would boil (p_{watvap}) in the surrounding environment. Avoidance of cavitation can be reasonably assured by selecting a propeller having certain geometric characteristics. A good empirical relationship that establishes these characteristics for propellers typified by the Wageningen B-Screw Series is the Keller Cavitation criterion [Ref. 2: p. 259]. It specifies the minimum required expanded area ratio ($A_E/A_{O\ min}$) to avoid cavitation and is given by:

$$(A_E/A_O)_{min} = \frac{(1.3 + 0.3Z)}{(p_{atm} + \rho \cdot acg\, h_{c\ell} - p_{watvap})} \cdot \frac{T}{D^2} + b \qquad (4.3)$$

where:

Z	=	number of blades;
T	=	developed thrust (lbf);
D	=	propeller diameter (ft);
p_{atm}	=	atmospheric pressure (psia);
p_{watvap}	=	fluid vaporization pressure (psia)
ρ	=	fluid density (lbf sec^2/ft^4)
acg	=	32.174 (ft/sec^2)
$h_{c\ell}$	=	depth to shaft centerline (ft)
b	=	constant: 0.1 for $Z = 2$, 0.2 for $Z = 1$.

As a constraint on the propeller selection, this requirement is writen as:

$$(A_E/A_O)_{min} \leq A_E/A_O \qquad (4.4)$$

or

$$G_{10}(\overline{X}) = \frac{(A_E/A_O)_{min}}{A_E/A_O} - 1 \leq 0 \qquad (4.5)$$

3. Strength

The final designer's consideration (for this study), included in the selection of a propeller, is that of strength.

Given the propeller's material (promat), selected from Table (II), and the loadings (T and Q_S) imposed, it is important to ensure that the blade's cross sections have proper dimensions (in an ideal sense, maximum blade section thickness (t*) and chord length (c)) to ensure adequate strength. Since the use of the B-Screw Series requires that the chord length (c) vary as a prescribed function of D, Z and A_E/A_O, as given in Table 1 of Reference [2], the adequacy for strength can be determined by an appropriately selected value for blade section maximum thickness-to-chord ratio (t*/c) alone. So, if t^*_{min} is the established minimum blade section maximum thickness, then the strength requirement follows from the constraint given by:

$$t^*_{min}/c \;=\; (t^*/c)_{min} \;\leq\; t^*/c \qquad (4.6)$$

The fact that blade section maximum thickness for the B-Screw Series varies linearly with the propeller radius (R) allows the strength constraint (equation (4.6)) to be evaluated at one section along the radius. This point is chosen to be at the 3/4 radius (.75R). Therefore, equation (4.6) becomes:

$$(t^*/c)_{.75R\ min} \;\leq\; (t^*/c)_{.75R} \qquad (4.7)$$

or

$$G_{11}(\bar{X}) \;=\; \frac{(t^*/c)_{.75R\ min}}{(t^*/c)_{.75}} - 1 \;\leq\; 0 \qquad (4.8)$$

Reference [2] suggests the following empirical relation for the minimum required equivalent blade section maximum thickness-to-chord ratio $(t^*/c)_{.75R\ min}$):

$$(t^*/c)_{.75R\ min} = \frac{Z\left\{0.0028+0.21\sqrt[3]{\dfrac{(2375-1125P/D)P_D}{4.123N_P D^3\left(S_c+\dfrac{D^2\ N_P^2}{12.788}\right)}}\right\}}{2.073\quad A_E/A_O} \tag{4.9}$$

where:

D	=	propeller diameter (ft);
P_D	=	delivered power (hp);
N_P	=	propeller revolution rate (rpm);
S_c	=	propeller material allowable stress (psi);
P/D	=	pitch-diameter ratio.

However, in Chapter VI of this thesis, an algorithm which employs the Schoenherr formulation [Ref. 8] with some modifications, is presented as an alternative to equation (4.9).

C. THE DESIGN VECTOR

In view of the preceding presentations on optimization and powering, the design vector $\bar{D}$ can be assembled for the general propeller selection problem utilizing the B-Screw Series. This vector is composed of preassigned parameters relating to environmental conditions, hull characteristics

and the propeller which are required for various equations and the design variables.

1. Parameters

a. Environmental

These parameters pertain primarily to the fluid conditions in which the propeller operates and to the atmosphere. Required for various calculations, they are:

1) fluid temperature (°F)--Temp

2) fluid density (lbf sec^2/ft^4)--ρ

3) fluid viscosity (ft^2/sec)--ν

4) fluid vaporization pressure (psia)--p_{watvap}

5) atmospheric pressure (psia)--p_{atm}

b. Hull Characteristics

These parameters pertain to certain details prescribed for the hull under study in the powering analysis. They are:

1) wake fraction--wt

2) thrust deduction--td

3) relative rotative efficiency --η_R

4) number of propellers--noscrw

5) shaft centerline depth (ft)--$h_{c\ell}$

6) propeller diameter limit (ft)--D_{lim}

c. Propeller

These parameters are specified in view of their discrete-valued nature. They are:

1) number of blades--Z

2) material--promat

Table (II) lists materials and properties considered in this study. These values are taken from Table (35), Section 15 of Reference [16].

TABLE II

Material Identifier Reference

promat	Material	Allowable Stress--Sc (psi)	Density--wd (lbf/in^3)
1	Cast Iron	3600--3950	.260
2	Cast Steel	5915--6265	.289
3	Type 2 Bronze	7200-7585	.305
4	Type 4 Ni-Al Bronze	8910--9430	.278
5	Stainless Steel	5400--5500	.283

2. <u>Design Variables</u>

In view of equations (3.13) through (3.17), the design variables common to all selection approaches are:

1) P_E
2) V
3) D
4) P/D
5) A_E/A_O
6) $(t^*/c)_{.75R}$
7) N_P
8) Q_S

The vectors $\bar{D}$ and $\bar{X}$ are shown schematically in figure (4.1).

$$\overline{D} = \begin{Bmatrix} \text{Temp} \\ \rho \\ \nu \\ P_{watvap} \\ P_{atm} \\ \text{wt} \\ \text{td} \\ \eta_R \\ \text{noscrw} \\ h_{c\ell} \\ D_{lim} \\ Z \\ \text{promat} \\ P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \\ N_P \\ Q_S \end{Bmatrix}$$

$$\overline{X} = \begin{Bmatrix} P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \\ N_P \\ Q_S \end{Bmatrix}$$

Figure 4.1 Design Vectors $\overline{D}$ and $\overline{X}$

D. CONSTRAINTS

Besides the constraints imposed by equations (4.2), (4.5) and (4.8), equations (3.25) through (3.31) are rearranged to the format of constraints in equation (2.9). They are listed as follows:

1) Equivalent Reynolds Number--Equation (3.25) becomes:

$$1 \leq \frac{Rn^*_{.75R}}{2 \times 10^6} \leq 1000 \tag{4.10}$$

Two constraints are derived:

$$G_3(\bar{X}) = 1 - \frac{Rn^*_{.75R}}{2 \times 10^6} \leq 0 \tag{4.11}$$

$$G_4(\bar{X}) = \frac{Rn^*_{.75R}}{2 \times 10^6} - 1000 \leq 0 \tag{4.12}$$

2) Expanded Area Ratio--Equations (3.27) through (3.31) become:

$$(A_E/A_O)_{lower}(Z) \leq A_E/A_O \leq (A_E/A_O)_{upper}(Z) \tag{4.13}$$

Two constraints are derived:

$$G_5(\bar{X}) = (A_E/A_O)_{lower}(Z) - A_E/A_O \leq 0 \tag{4.14}$$

$$G_6(\bar{X}) = A_E/A_O - (A_E/A_O)_{upper}(Z) \leq 0 \tag{4.15}$$

3) Advance Ratio--Equation (3.22) becomes:

$$0 \leq \frac{J}{1.6} \leq 1 \tag{4.16}$$

Two constraints are derived:

$$G_1(\bar{X}) = \frac{-J}{1.6} \leq 0 \tag{4.17}$$

$$G_2(\bar{X}) = \frac{J}{1.6} - 1 \leq 0 \tag{4.18}$$

4) Equivalent Blade Section Maximum Thickness-to-Chord Ratio--Using equation (3.19), boundaries on the range of $(t^*/c)_{.75R}$ are defined by:

$$\tfrac{1}{2}(t/c)_{.75R} \leq (t^*/c)_{.75R} \leq 4(t/c)_{.75R} \tag{4.19}$$

Two constraints are derived:

$$G_7(\bar{X}) = \tfrac{1}{2}(t/c)_{.75R} - (t^*/c)_{.75R} \leq 0 \tag{4.20}$$

$$G_8(\bar{X}) = (t^*/c)_{.75R} - 4(t/c)_{.75R} \leq 0 \tag{4.21}$$

E. OBJECTIVE FUNCTIONS

Upon consideration of equation (3.13), Design Case No. 1 and Design Case No. 2 require that the open water efficiency (η_o), given by equation (3.11), be <u>maximized</u>. In terminology related to optimization, this is stated as:

$$OBJ_{1,2} = -\eta_o \tag{4.22}$$

Design Case No. 3, the "matching" problem, requires that the blade weight (bldwt) be minimized. This is stated as:

$$OBJ_3 = \text{bldwt} \tag{4.23}$$

F. PROPELLER SELECTION OPTIMIZATION PROBLEM STATEMENT

As a general, non-linear constrained optimization problem to be solved by COPES/CONMIN, the propeller selection problem for all Design Cases may be stated as one equation given by:

$$\begin{aligned} &\text{Minimize:} \quad F(\overline{X}) = OBJ_{1,2} \text{ or } OBJ_3 \\ &\text{Subject to:} \quad G_j(\overline{X}) \leq 0 \qquad j = 1,\ldots,12 \\ &\qquad X_i^{lower} \leq X_i \leq X_i^{upper} \qquad i = 1,\ldots,8 \end{aligned} \tag{4.24}$$

The constraint $G_{12}(\overline{X})$ and the values for X_i^{lower} and X_i^{upper} will be specified according to each Design Case.

G. CODING FUNDAMENTALS

1. GLOBCM Common Block

The GLOBCM common block, required by COPES/CONMIN, is now assembled. Table (III) specifies the assignment locations for the FORTRAN variables which define objective functions, design variables and constraints.

2. SUBROUTINE ANALIZ

While each Design Case uses a different approach, all analyses are very similar. Therefore, each SUBROUTINE

TABLE III

Global Common (GLOBCM) Catalog

Global Location	FORTRAN Name	DEFINITION
1	ETAO	η_o
2	WEIGHT	bldwt
3	AEDVAO	A_E/A_O
4	DIA	D
5	N	$N_P = 60 \cdot n_P$
6	PE	P_E
7	PDIVD	P/D
8	QS	Q_S
9	TC75R	$(t^*/c)_{.75R}$
10	V	V (ft/sec)
11	RJCHL	$G_1(\bar{X})$--eqn (4.17)
12	RJCNU	$G_2(\bar{X})$--eqn (4.18)
13	R75RCL	$G_3(\bar{X})$--eqn (4.11)
14	R75RCU	$G_4(\bar{X})$--eqn (4.12)
15	AEAOCL	$G_5(\bar{X})$--eqn (4.14)
16	AEAOCU	$G_6(\bar{X})$--eqn (4.15)
17	TC75CL	$G_7(\bar{X})$--eqn (4.20)
18	TC75CU	$G_8(\bar{X})$--eqn (4.21)
19	POWBAL	$G_{12}(\bar{X})$--eqn (7.10) or (8.11) or (9.4)
20	DIACNU	$G_9(\bar{X})$--eqn (4.2) or (9.6)
21	AEAOCV	$G_{10}(\bar{X})$--eqn (4.5)
22	TCSTRS	$G_{11}(\bar{X})$--eqn (4.8)
23	RJ	J

ANALIZ shares a common structure and other common subroutines which perform calculations required in all cases. Appendices C, F and I contain, respectively, the source listings of SUBROUTINE ANALIZ for Design Case No. 1, Design Case No. 2 and Design Case No. 3.

a. Structure

The structure common to all cases follows accordingly:

1) all initialization of environmental, hull and propeller parameters is accomplished in the input section (ICALC = 1).

2) evaluation of K_T and K_Q, all constraints and appropriate objective functions ($-\eta_o$ or bldwt) are accomplished in the execution section (ICALC = 2).

3) output of results for each optimization problem is accomplished in the output section (ICALC = 3).

b. Basic Subprograms

The following FORTRAN subprograms are used in all three SUBROUTINE ANALIZ codes:

1) SUBROUTINE CH75RA--calculates the equivalent blade section chord length ($c_{.75R}$) for the propeller using Table 1 [Ref. 2, p. 252].

2) SUBROUTINE REY75R--calculates the equivalent Reynolds number ($Rn^*_{.75R}$) using equations (3.19) and (3.20).

3) SUBROUTINE COEFSA--calculates the thrust and torque coefficients (K_T and K_Q) through sequential calls to SUBROUTINE CALCKT and SUBROUTINE CALCKQ. The polynomial expressions

(Tables (5) and (6), [Ref. 2]) for these coefficients are contained in SUBROUTINE CALCKT and SUBROUTINE CALCKQ respectively.

4) SUBROUTINE OPWEFF--calculates the open water efficiency (η_o) using equation (3.11).

5) SUBROUTINE JCNA--calculates the constraints on the advance ratio (J) given by equations (4.17) and (4.18).

6) SUBROUTINE REYCNA--calculates the equivalent Reynolds number constraints given by equations (4.11) and (4.12).

7) SUBROUTINE EXTCCN--calculates the constraints on expanded area ratio (A_E/A_O) and equivalent blade section maximum thickness-to-chord ratio ($t^*/c_{.75R}$) given by equations (4.14), (4.15), (4.20) and (4.21).

8) SUBROUTINE DICNUA--calculates the constraint on the propeller diameter (D) given by equation (4.2) using the hull parameter on maximum diameter (D_{lim}).

9) SUBROUTINE CAVCNA--calculates the constraint for cavitation given by equation (4.5) using equation (4.3).

10) SUBROUTINE STRCNA--calculates the constraint for strength given by equation (4.8) using equation (4.9).

H. SUMMARY

The propeller selection problem has now been formulated as a constrained optimization problem which can be solved by COPES/CONMIN. Two items remain for discussion before proceeding to specify the final details pertaining to each SUBROUTINE ANALIZ code and to present numerical examples. These items are:

1) the theory and coding relating to the computation of the propeller's blade weight for the evaluation of the objective function in Design Case No. 3 (OBJ_3).

2) the theory and coding relating to the computation of the minimum required equivalent blade section maximum thickness-to-chord ratio ($t^*/c_{.75\ min}$) for use in the alternative evaluation of the strength constraint given by equation (4.8).

V. PROPELLER BLADE WEIGHT--AN OBJECTIVE FUNCTION

A. INTRODUCTION

In this chapter, the method for the computation of the propeller's blade weight (bldwt), the objective function OBJ, is examined. First, a brief overview on the steps in the computational procedure is presented. The FORTRAN subprogram SUBROUTINE WGTCAL developed from the algorithm is then described. Again, Appendix B contains all subprogram listings.

B. THEORY AND PROCEDURE

Given the material of a propeller, the calculation of the weight of one blade involves nothing more than a volume calculation, a relatively routine task performed by most naval architects/marine engineers. Analagous to the determination of the underwater volume of a ship's hull, the calculation is an integration of blade section profiles' cross-sectional areas over the propeller radius (R).

1. Limits of Integration

Figure (5.1) depicts a side elevation view of a blade and hub, parallel to the propeller shaft axis. The cross-hatched area indicates the trace of the volume to be calculated. In view of equations (3.32) and (3.33), limits of integration are from $r = .167R$ to $r = R$ for $Z = 4,5,6$ and $r = .18R$ to $r = R$ for $Z = 3,7$. For convenience, a non-dimensional variable "x" will be defined as:

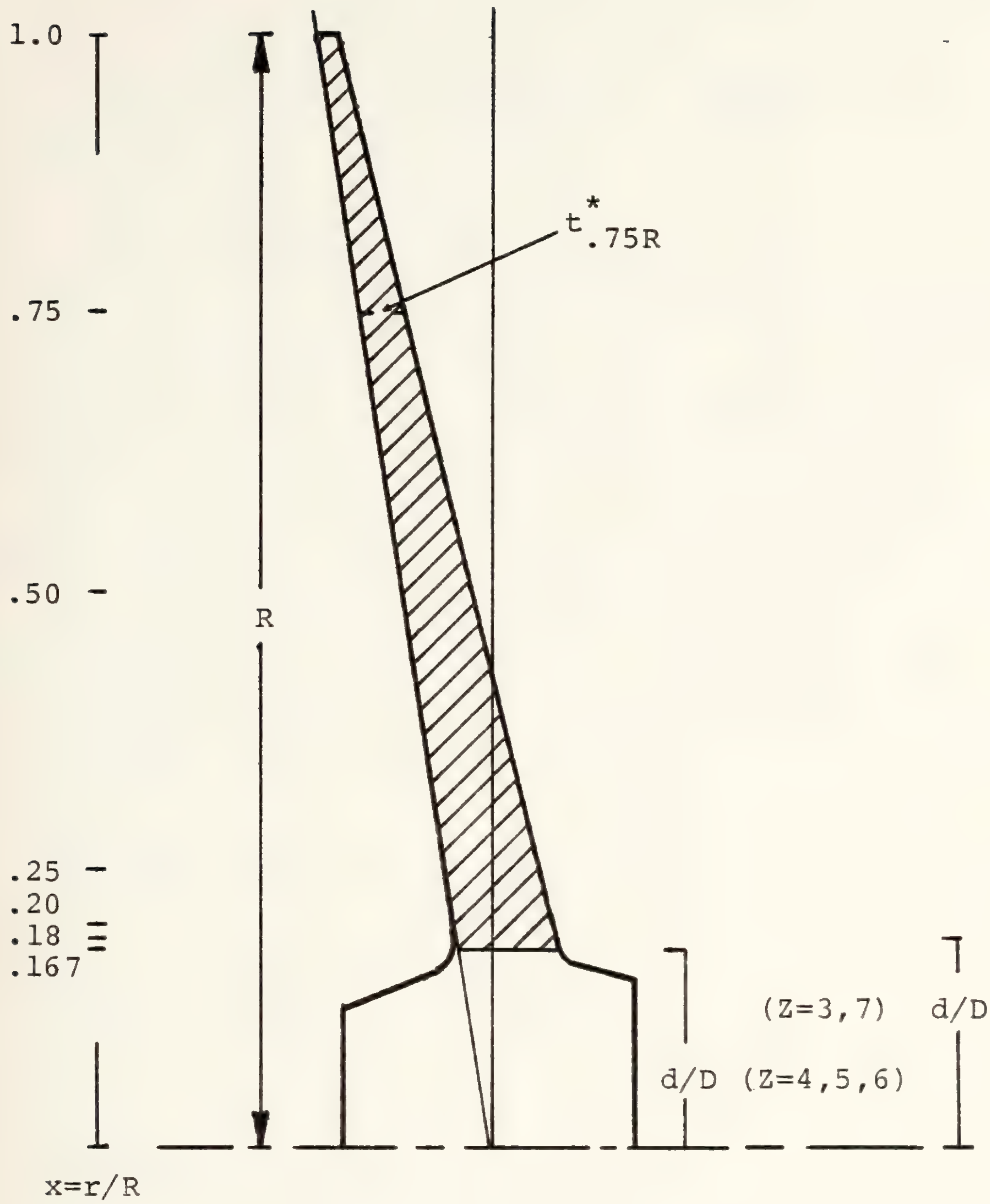

Figure 5.1 Propeller Blade & Hub--Side View

$$x = \frac{r}{R} \qquad (5.1)$$

Limits are now expressed as $x = .167$ or $.18$ to $x = 1.0$. Quite obviously, $R = (D/2.0)$.

2. Blade Section Profile

Figure (5.2) depicts an expanded cylindrical blade section in profile view at a given r or x. For the Wageningen B-Screw Series, the profile is defined, geometrically, by a succession of vertical ordinates which specify points along the blade section's profile on the "face" (y_f) and on the back (y_b) with respect to the pitch reference line. At any $r = xR$, vertical ordinates for "aft" ($P \leq 0$) and "fwd" ($P > 0$) portions of the blade section are determined by:

$$y_{fa} = V_1(t^* - t^*_{te}) \qquad P \leq 0 \qquad (5.2)$$

$$y_{ba} = (V_1 + V_2)(t^* - t^*_{te}) + t^*_{te} \qquad P \leq 0 \qquad (5.3)$$

and

$$y_{ff} = V_1(t^* - t^*_{\ell e}) \qquad P > 0 \qquad (5.4)$$

$$y_{bf} = (V_1 + V_2)(t^* - t^*_{\ell e}) + t^*_{\ell e} \qquad P > 0 \qquad (5.5)$$

where:

V_1, V_2 = tabulated values depending on x and P (see Tables (2) and (3), Ref. [2]);

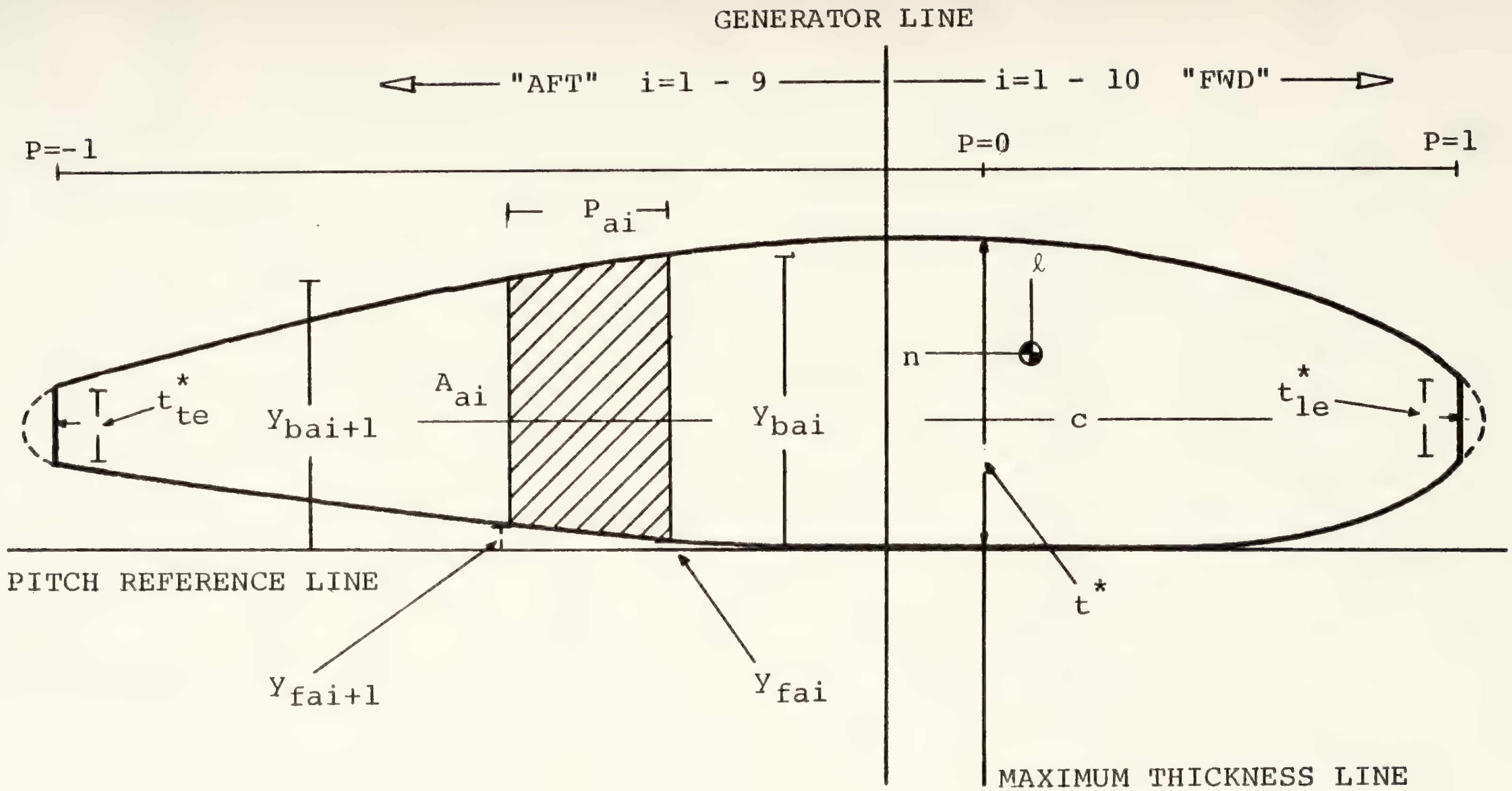

Figure 5.2 Expanded Cylindrical Blade Section--Profile View

$t^*_{\ell e}$ = blade section leading edge thickness (ft);

t^*_{te} = blade section trailing edge thickness (ft).

Units for y_{fa}, y_{ba}, y_{ff} and y_{bf} are feet (ft). For this study, a reasonable assumption is made in that:

$$t^*_{\ell e} = t^*_{te} = (\frac{1}{10})\ t^* \tag{5.6}$$

3. Blade Section Cross-Sectional Area

The cross-sectional area at each x = r/R (A(x)) is determined by:

$$A(x) = \sum_{i=1}^{9} A_{ai} + \sum_{i=1}^{10} A_{fi} \tag{5.7}$$

where

$$A_{ai} = \Delta P_{ai} \{\frac{h_{ai+1} + h_{ai}}{2}\} \tag{5.8}$$

$$h_{ai} = y_{bai} - y_{fai} \tag{5.9}$$

$$h_{ai+1} = y_{bai+1} - y_{fai+1} \tag{5.10}$$

Expressions for A_{fi}, h_{fi} and h_{fi+1} follow in similar fashion.

Values for y_{fai} and y_{bai} are determined at 9 points along the "aft" portion of a given blade section's chord (c): values of y_{ffi} and y_{bfi} are determined at 10 points along the

"fwd" portion. The values for ΔP_{ai} and ΔP_{fi} are fractional values of the blade section's chord length (c) at radius $r = xR$ as determined from Tables (2) and (3) in Reference [2]. The units for A(x) are square feet (ft^2). Units for h_{ai}, h_{ai+1}, h_{fi}, h_{fi+1}, c, ΔP_{ai} and ΔP_{fi} are feet (ft).

4. Volume Integration

The blade volume (bldvol) is finally determined by using Simpson's Rule for integration of A(x) along the non-dimensional radius x using appropriate limits.

5. Blade Weight

Once the blade volume (bldvol) is calculated, the weight (bldwt) is determined by:

$$\text{bldwt} = \text{bldvol} \cdot \text{wd} \cdot 1728 \tag{5.11}$$

where:

bldvol = volume of one blade (ft^3);

wd = material weight density (lbf/in^3).

Weight Density (wd) depends on blade material (promat). Table (II) lists appropriate values.

C. CODING

SUBROUTINE WGTCAL is the main subprogram for the blade weight calculation. It, in turn, calls the following FORTRAN subprogram for various calculations:

1) SUBROUTINE TDIST--generates, at specified radius values, a distribution of blade section maximum thicknesses (t^*).

2) SUBROUTINE BLDPRP--generates, at specified radius values (i.e., r = .167R or .18R, .2R, .3R, .4R, ..., .9R, 1.0R), various "blade section properties", one of which is a blade section's cross-sectional area given by equation (5.7). Other properties which are determined (for later use in direct stress computations) include blade section chord lengths and centroids and "critical point" locations as defined in Chapter VI.

3) SUBROUTINE BLDVOL --performs a Simpson's Rule integration for the propeller blade volume (bldvol) using blade section cross-sectional areas generated in SUBROUTINE BLDPRP. The blade weight (bldwt) is computed as a final step in the main subprogram SUBROUTINE WGTCAL.

Examination of the codes in Appendix B reveals extensive use of common blocks for passing data from one subprogram to another. Comment cards provide a full definition of all common blocks as well as a description of the task being performed at various points in a given subprogram.

D. SUMMARY

The coding developed for this study is, admittedly, not very compact and efficient. However, the intention has been to write all codes with sufficient documentation in order to facilitate the reader's understanding of the algorithms employed as well as to make the author's debugging work easier.

VI. THICKNESS-TO-CHORD RATIO--A DESIGN CONSTRAINT

A. INTRODUCTION

The purpose of this chapter is to examine the development of an algorithm that will be used to determine the minimum required equivalent blade section maximum thickness-to-chord ratio used in equation (4.8). The formulation is based upon the method developed by Dr. Karl E. Schoenherr [Ref. 8] in 1963. After a review of the past and present methods employed in propeller strength analysis is conducted, a description of the Schoenherr model and a list of the assumptions used with that model is presented. Then, a brief restatement of his model's equations which are used in the algorithm is followed by a derivation of the author's modifications to the Schoenherr method. The chapter is completed by conducting a review of the theory and coding employed by the algorithm.

The principal reference which is cited throughout this chapter is, again, Reference [8]. The reader is encouraged to review this reference for further details.

B. PROPELLER STRENGTH ANALYSIS--A HISTORICAL REVIEW

Marine propeller blades present a special class of structural problem. That problem lies in the difficulty of describing a blade design in simple mathematical terms for subsequent analysis through various means. Until the "finite element method era", analytical methods, including the one

[Ref. 8] adapted for this study, relied heavily on practical experience of the propeller designer and semi-theoretical considerations. Analysis by these methods provided a criterion of stress rather than actual computation of stresses. These methods for predicting blade stresses were developed by using "beam" theory or "shell" theory.

The use of elementary beam theory in propeller strength analysis was first adopted by Taylor [Ref. 22]. He treated a blade as a cantilever beam attached to the propeller hub and loaded by thrust and torque forces distributed linearly over the propeller radius. His approach is often deemed a "modified beam theory" because he chose to calculate the direct stresses using the moment of inertia properties of expanded cylindrical blade sections with neutral axis parallel to the nose-tail (pitch-reference) line or chord of that expanded section. Reasonable estimates of stresses along the blade surface were achieved for the unraked, unskewed and narrow-bladed propellers of his time.

As propellers "modernized" and became skewed and wider with increasing rake (mostly aft), modifications, improvements and alternatives to Taylor's theory were developed. Principally, modifications by Rosingh [Ref. 23] and Hancock [Ref. 24] proposed using moment of inertia properties of a blade section that was normal to the generating line of the axially projected blade outline. Romson [Ref. 25] later improved Taylor's theory for application to wide-bladed

propellers. Morgan [Ref. 26] provided an improved method for calculating the geometric properties of "modern" airfoil-shaped blade sections. Aernoldus and Keyser's [Ref. 27] "quasi-static" modeling of the propeller blade allowed for additional consideration to stresses induced by centrifugal loading of the raked and skewed blade. The beam theory approaches to propeller blade stress analysis culminated, for all practical purposes, with Schoenherr's work [Ref. 8] in 1963.

Alternatives to Taylor's beam theory approach, prior to 1963, consisted of the application of "shell" theory to the propeller blade strength problem. This approach was first proposed by Conn [Ref. 28] and subsequently formulated by Cohen [Ref. 29] who modeled the blade as a helicoidal shell with variable thickness and infinite width. "Shell Theory" was utilized again in experimental studies by Connolly [Ref. 30] who, like his predecessors, was also forced into making an assumption about the behavior of the displacements of the blade sections (i.e., constant displacements normal to the constant pitch blade at each fractional radius distance from the hub) beyond usual assumptions of shell theory. Essentially, his experimental results on one specific propeller contradicted the computational values. Attempts at a generalized numerical solution to Connolly's equations appeared in 1963 [Ref. 31] and 1964 [Ref. 32]. In 1968, Atkinson [Ref. 33], compared Connolly's results with currently

adopted cantilever beam methods and found, based on the inconsistency of results, that it was not possible to recommend one method over the other in the blade strength design procedure; another approach was needed.

Commenting on Atkinson's paper at that time, Sontvedt [Ref. 34] pointed out that, in view of these inconsistencies, the only approach to blade strength analysis which did not require very broad assumptions was the finite element technique. Developments in the method at that time were providing a new and powerful tool for structural analysis. The propeller blade was just another application. Genalis [Ref. 35] developed codes for the determination of displacements and stresses in a blade under hydrodynamic loads using the FEM technique and modeling the blade as a shell, a 3-D element mesh of tetrahedrons and rectangular prisms and, finally, a composite of shell and 3-D elements. As an aside, a finite "difference" solution to Connolly's analytical equations was proposed in 1972 [Ref. 36]. In 1973, Atkinson [Ref. 37] reported the application of both hydrodynamic and centrifugal loads to a blade modeled by a thin-shell triangular mesh and a thick-shell parabolic and cubic curved element mesh. The results of the triangular element were considered unsatisfactory. Another use of the thin-shell triangular element was reported by Sontvedt [Ref. 34] in 1974 using the SESAM-69 code [Ref. 38].

The need to model the blade correctly near the hub, where root stresses are usually critical, necessitated the

consideration of 3-D elements in lieu of thick/thin-shell elements [Refs. 39,40]. The use of the 4- and 10-noded tetrahedral element (i.e., TET-4, TET-10 respectively) to construct a blade mesh was conducted by Beek [Refs. 41,42]. He observed that improved accuracy of stress values, achieved by the use of these meshes, were overshadowed somewhat by the extensive storage capacity required for each analysis. Another "natural" improvement, from a geometrical standpoint, appeared in 1978. A general 3-D curved isoparametric element was incorporated in a computer code [Ref. 43] developed by Ma based on his previous formulation work [Ref. 44].

The finite element approach will continue to grow in use in propeller blade strength analysis with each successive improvement made to the basic elements which are used in the mesh generation of the blade. But, until the computer storage problem is resolved to the point where one mesh generation and subsequent stress analysis of one particular blade becomes a minor processing task, the basic analytical techniques will continue to be a meritable "check" [Ref. 45] in the preliminary (or conceptual) phase of propeller selection/design. In this context, the method formulated by Schoenherr and his colleagues twenty years ago is considered for adoption in determining a minimum required blade section maximum thickness-to-chord ratio.

C. SCHOENHERR'S METHOD

1. Background

Schoenherr's method is applicable to preliminary (or, conceptual) propeller selection problems because it employs an assumed thrust and torque force loading distribution for the propeller blade. This assumption is made at this stage of the ship's design because the exact wake velocity distribution at the propeller race is generally not known.

Also, his method is applicable to propellers represented by the Wageningen B-Screw Series because the blades of these propellers meet Schoenherr's criteria for the blade types covered by his formulation. Specifically, B-Screw Series blades have:

1) a small constant rake angle of 15° over the entire blade radius;

2) a constant pitch distribution over the propeller radius with the exception of the Z = 4 propeller whose pitch is slightly reduced near the hub;

3) mild skew;

4) linear distribution of blade section maximum thickness over the radius of the blade;

5) aerfoil profile qualities where the nose-tail line or the chord of the blade section is approximately parallel to the pitch reference line.

2. The Blade Model

Schoenherr models the propeller blade as a cantilever beam with unsymmetrical and variable area cross sections subjected to loading distributions of hydrodynamic and centrifugal forces. The following additional assumptions apply:

1) Flexure theory applies. This subsequently implies the following: a) plane cross sections remain plane under load, b) Hooke's Law is valid, c) the blade material is homogeneous and isotropic, d) fibers are free to extend and contract independently of adjacent fibers, and e) stresses at a point arising from various forces superimpose.

2) Shearing stresses and their effects are neglected. Only the direct stresses on a strength section are taken into account.

3) The strength sections are taken to be the expanded cylindrical blade sections at various radial locations.

4) The neutral axes of a strength section are straight lines passing through the centroid of the expanded cylindrical blade section and are parallel and normal, respectively, to the pitch reference line, and therefore, the chord, at each blade section.

5) Bending Moments are applied in two planes which are mutually perpendicular to each other. One plane is normal to the pitch-reference line (and chord) of the strength section; the other is parallel.

6) The angle between the principal axes of inertia and the neutral axes is zero.

Using this model and assumptions, Schoenherr applies the following formula for the evaluation of the direct fiber stress ($[\sigma_o]$) in a blade section at a radius $r = r_o$:

$$[\sigma]_o = \frac{[M]_{no}\, u_o}{I_{no}} + \frac{[M]_{\ell o}\, w_o}{I_{\ell o}} + \frac{[F_c]_o}{A(x_o)} \qquad (6.1)$$

where:

$[M]_{no}$, $[M]_{\ell o}$ = resultant bending moments in planes normal ($[M]_{no}$) and parallel ($[M]_{\ell o}$ to the strength section's chord at $r = r_o$ (ft-lbf);

$[F_c]_o$ = centrifugal force acting normal to the plane of the strength section at $r = r_o$ and resulting from the centrifugal acceleration of the remaining blade element mass above that strength section (lbf);

u_o, w_o = coordinates of a point on the strength section's periphery with respect to that section's neutral axes system (ℓ-n system) (ft);

$A(x_o)$ = strength section's cross-sectional area (ft^2);

$I_{\ell o}$ = moment of inertia of the strength section with respect to the "ℓ" axis (ft^4);

I_{no} = moment of inertia of the strength section with respect to the "n" axis (ft^4);

x_o = non-dimensional radius given by $x_o = r_o/R$.

Since equation (6.1) indicates that the direct fiber stress is greatest at points on the periphery of the strength section, Schoenherr selects to examine four "critical points"

on the periphery where the fiber stress is likely to be a maximum. These points are designated as 1, 2, 3 and 4 on Figure (6.1) and are specified by coordinates (u1,w1), (u2,w2), (u3,w3) and (u4,w4) respectively in the "ℓ-n" reference system.

The values for $[M]_{no}$ and $[M]_{\ell o}$ are determined by the following relation:

$$[M]_{no} = [M_P]_{no} + [M_{cb}]_{no} \tag{6.2}$$

$$[M]_{\ell o} = [M_P]_{\ell o} + [M_{cb}]_{\ell o} \tag{6.3}$$

where:

$[M_P]_{no}$ = total bending moment due to hydrodynamic loading acting in a plane normal to a strength section's chord at $r = r_o$ (ftlbf);

$[M_P]_{\ell o}$ = total bending moment due to hydrodynamic loading acting in a plane parallel to a strength section's chord at $r = r_o$ (ftlbf);

$[M_{cb}]_{no}$ = total bending moment due to centrifugal loading acting in a plane normal to a strength section's chord at $r = r_o$ (ftlbf);

$[M_{cb}]_{\ell o}$ = total bending moment due to centrifugal loading acting in a plane parallel to a strength section's chord at $r = r_o$ (ftlbf).

3. Bending Moments Due to Hydrodynamic Loading

The derivations of $[M_P]_{no}$ and $[M_P]_{\ell o}$ follow directly from Part I of Schoenherr's paper [Ref. 8: p. 83-89] and,

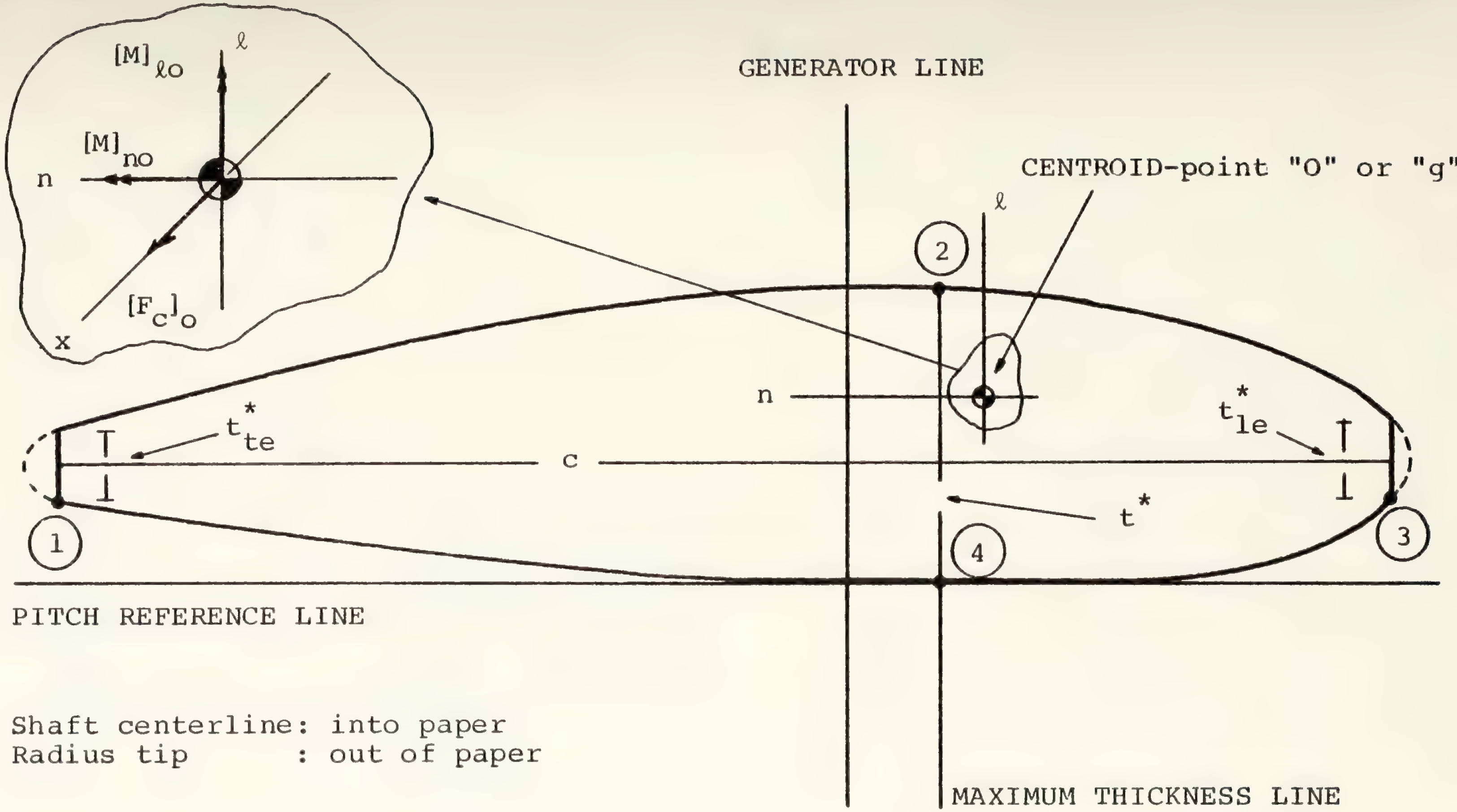

Figure 6.1 Strength Section at $r = r_o$

therefore, only key equations will be restated. References to equations which contain no decimal point apply to equations as numbered in his paper.

Thrust and torque force are components of the hydrodynamic "lifting" force acting on a blade. Using an assumed non-linear distribution of thrust along the blade radius given by equation (2), Schoenherr derives the following expression for the bending moment due to thrust ($[M_t]_o$) which acts at a blade section located at ratius $r = r_o$:

$$[M_t]_o = \frac{TR}{Z} \cdot \frac{\phi_2(x_o)}{\phi_1(x_h)} \tag{6.4}$$

where:

T	=	propeller thrust (lbf);
R	=	propeller radius (ft);
Z	=	no. of blades;
$\phi_2(x_o), \phi_1(x_h)$	=	functions of non-dimensional radius x evaluated at $x_o = r_o/R$ and $x_h = 0.2$ and given by equations (4) and (9).

For the bending moment due to torque ($[M_q]_o$) which acts at a blade section located at radius $r = r_o$, Schoenherr derives the following:

$$[M_q]_o = \frac{Q_P}{Z} \cdot \frac{\psi_2(x_o)}{\phi_1(x_h)} \tag{6.5}$$

where:

Q_P = propeller torque (ft-lbf);

Z = no. of blades;

$\psi_2(x_o), \phi_1(x_h)$ = functions of non-dimensional radius x evaluated at $x_o = r_o/R$ and $x_h = 0.2$ and given by equations (19) and (4).

Figure (6.2) depicts the component resolution for $[M_P]_{no}$ and $[M_P]_{\ell o}$ which results when equations (6.4) and (6.5) are imposed at a strength section at $r = r_o$ which has a pitch angle β_o. The following relations are derived as equations (42) and (43) in Schoenherr's paper:

$$[M_P]_{no} = [M_t]_o \cos \beta_o + [M_q]_o \sin \beta_o \tag{6.6}$$

$$[M_P]_{\ell o} = [M_t]_o \sin \beta_o - [M_q]_o \cos \beta_o \tag{6.7}$$

4. Force and Bending Moments Due to Centrifugal Loading

The derivation and expressions contained in this section constitute the author's modifications to the formulation in Part II of Schoenherr's paper. In Part II, Schoenherr's derivations for $[M_{cb}]_{no}$ and $[M_{cb}]_{\ell o}$ are formulated for computation using a propeller drawing. This follows from the fact that his method, which was funded by the American Bureau of Shipping, was intended to be used as that classification society's "designer's check" on adherence to the Bureau's strength criteria from a propeller blueprint. To evaluate the direct fiber stresses from equation (6.1) for the Wageningen B-Screw Series in accordance with Schoenherr's

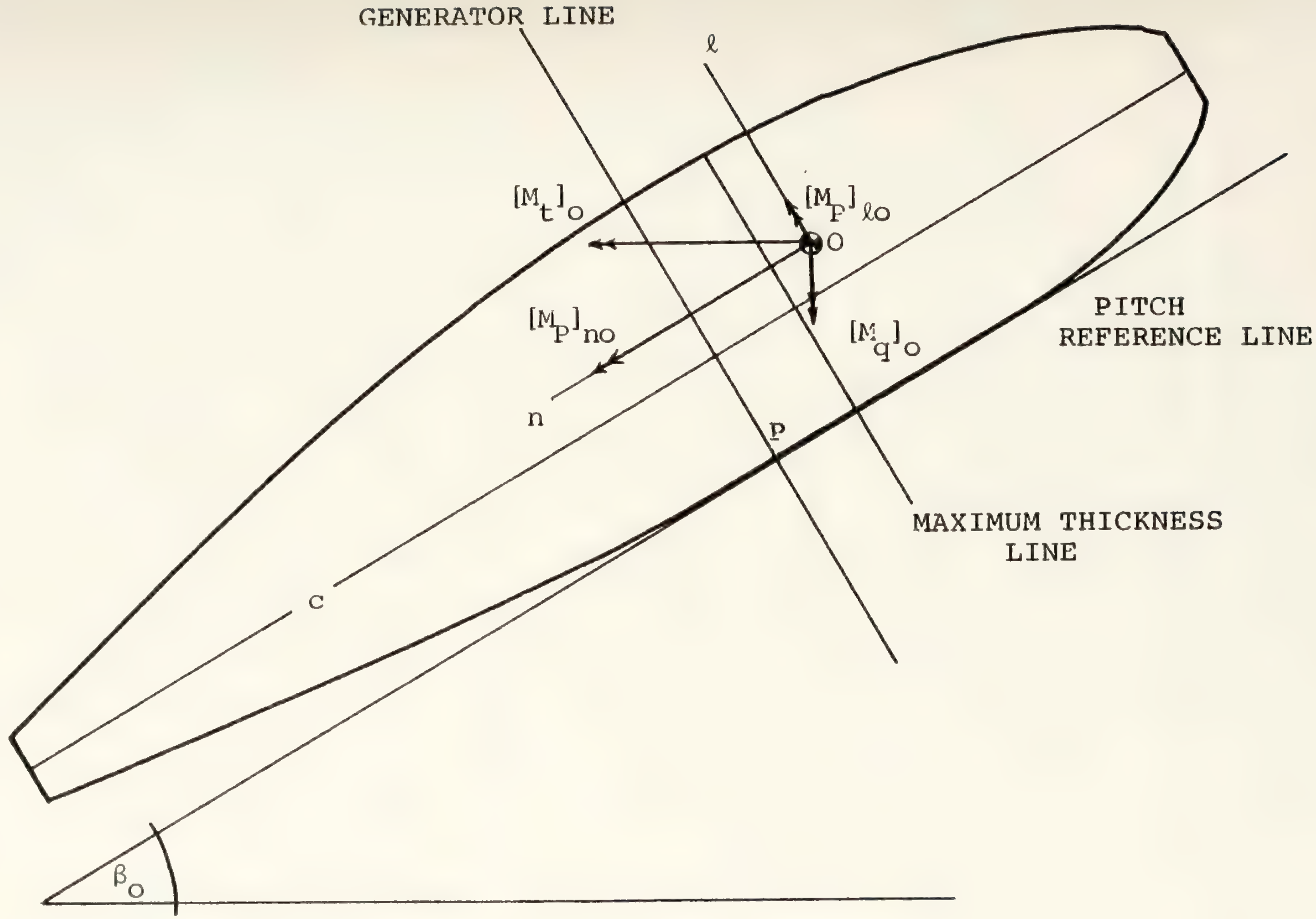

Figure 6.2   Bending Moments due to Thrust and Torque

method, $[M_{cb}]_{no}$ and $[M_{cb}]_{\ell o}$ must be evaluated from expressions derived from the available information on blade section profiles and other geometric characteristics which are contained in Reference [2] and previously used in Chapter V.

Consider Figure (6.3) where the centrifugal force $[C_F]_o$ of a blade element above a blade section at $x = x_o = r_o/R$ acts in a radial direction from the shaft centerline. Its line of action passes through point "N", which is on the same cylindrical surface as the blade section at $x = x_o = r_o/R$, and through point "G", which is the center of gravity of the blade element above the blade section at $x = x_o = r_o/R$. From the figure, the following expression is derived:

$$[C_F]_o = [C_F]_o \cos \zeta(x_o) + [C_F]_o \sin \zeta(x_o) \qquad (6.8)$$

$[C_F]_o$ is shifted to point "N" and is decomposed into components $[C_F]_o \cos \zeta(x_o)$ and $[C_F]_o \sin \zeta(x_o)$. The entire cylindrical surface in which the blade section at $x = x_o = r_o/R$ and point "N" lie is now expanded into a flat plane for further consideration (see Figure (6.4)). In this configuration, $[C_F]_o \cos \zeta(x_o)$ is normal to this flat plane while $[C_F]_o \sin \zeta(x_o)$ lies in this plane.

Let point "O" be the location of the blade section's neutral axes system (i.e., the ℓ-n system). Then, the forces and moments due to the centrifugal reaction of the blade element above this section act at point "O" and are given by:

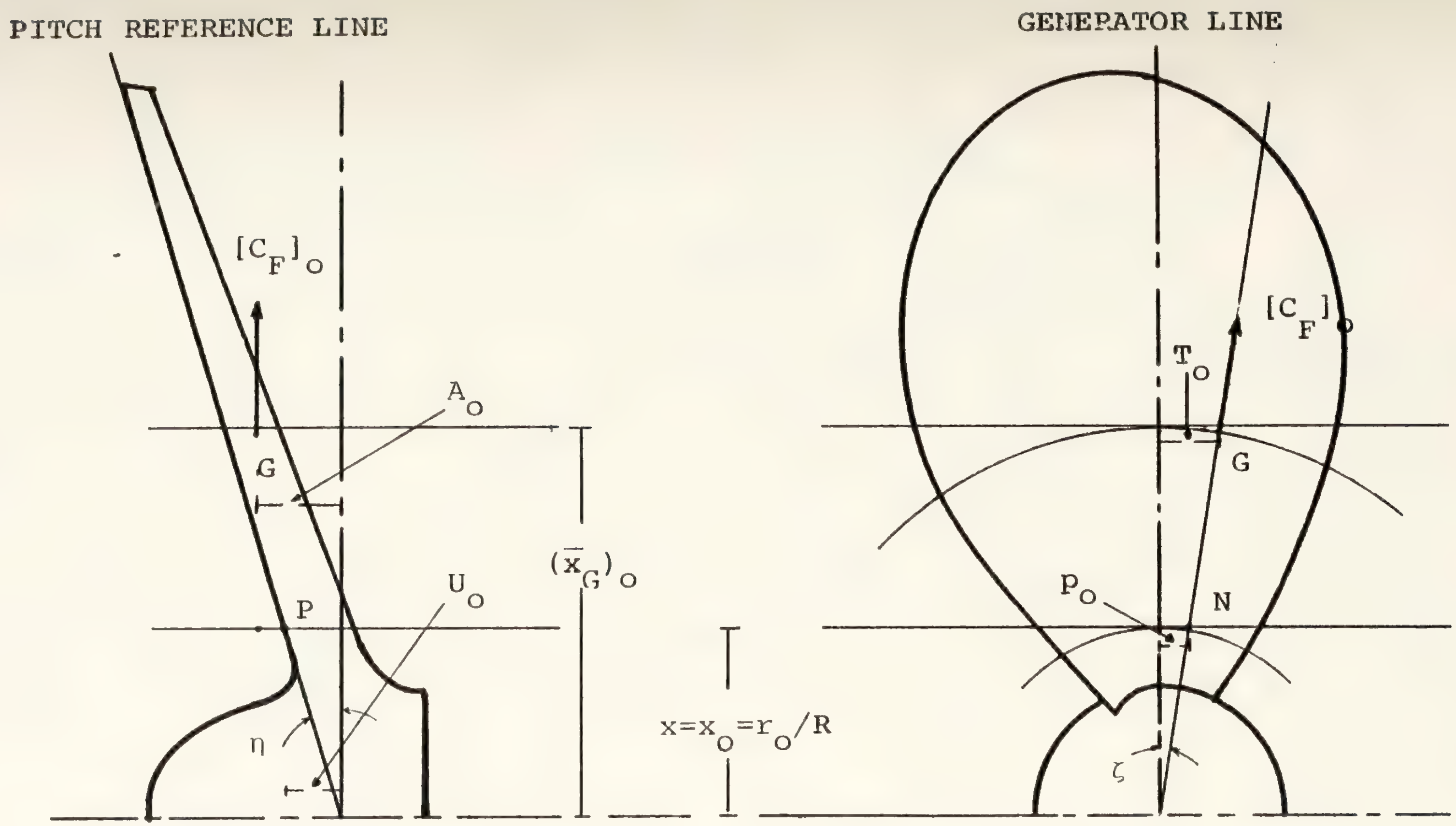

Figure 6.3 Center of gravity "G" and intersection point "N"

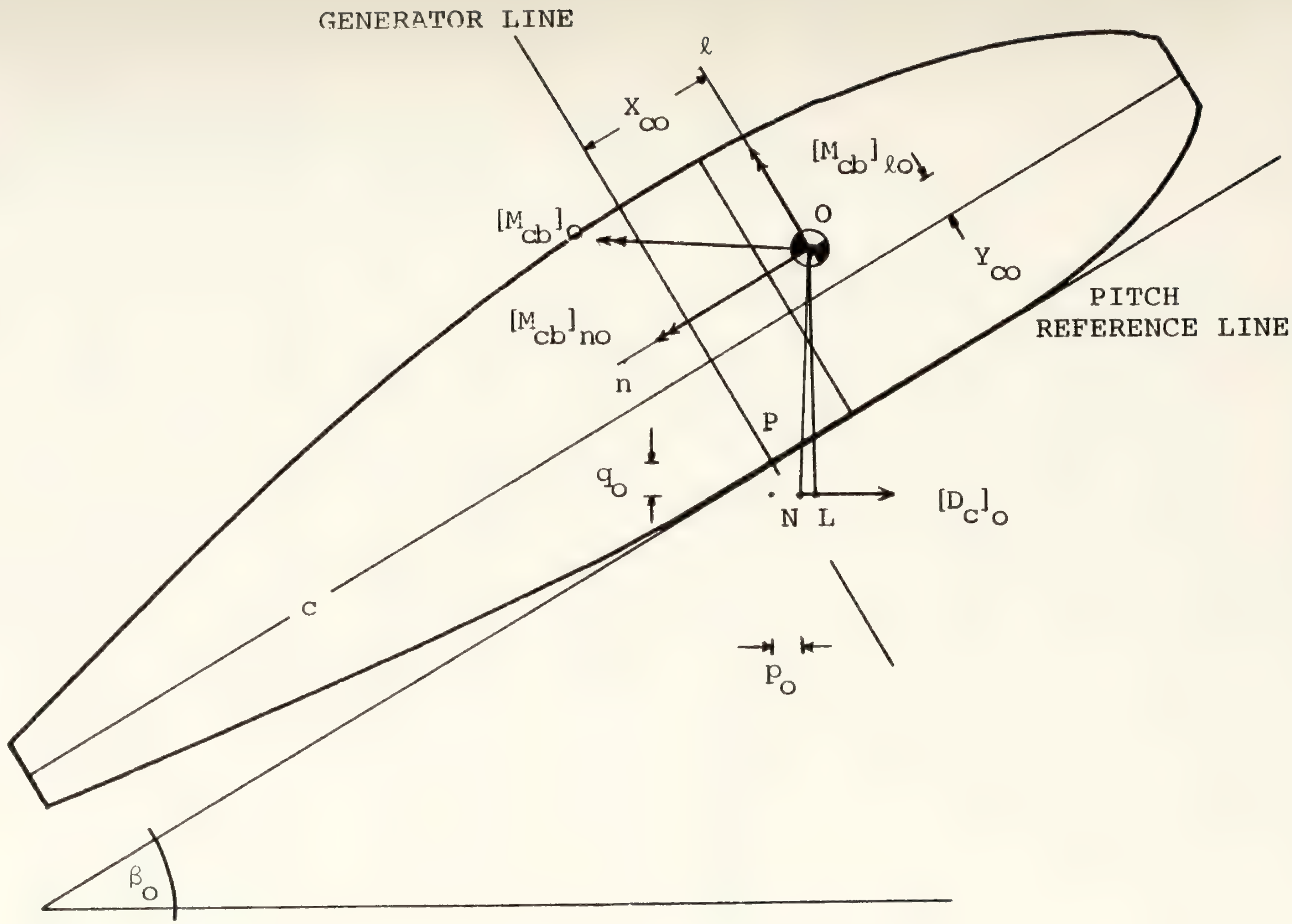

Figure 6.4 Internal Loading on a Blade Section at $x = x_o = r_o/R$

$$[F_c]_o = [C_F]_o \cos\zeta(x_o) \qquad (6.9)$$

$$[D_c]_o = [C_F]_o \sin\zeta(x_o) \qquad (6.10)$$

$$[M_{cb}]_o = [F_c]_o \cdot \overline{NO} \qquad (6.11)$$

$$[M_{cw}]_o = [D_c]_o \cdot \overline{LO} \qquad (6.12)$$

where:

$[F_c]_o$ = direct force, due to centrifugal action, acting on the blade section located at $x = x_o = r_o/R$;

$[D_c]_o$ = shear force, due to centrifugal action, acting on the blade section located at $x = x_o = r_o/R$;

$[M_{cb}]_o$ = bending moment at point "O" imposed by $[F_c]_o$ acting through point "N";

$[M_{cw}]_o$ = torsional moment at point "O" imposed by $[D_c]_o$ acting through point "N".

Since Schoenherr's method does not consider shear forces and their effects, $[D_c]_o$ and $[M_{cw}]_o$ will not be considered in this modification. However, $[F_c]_o$ and $[M_{cb}]_o$ must now be computed for each blade section along the propeller's radius in order to account for their contributions to equations (6.2), (6.3) and, finally, in equation (6.1).

The computation is derived as follows. Consider Figure (6.4). Again, $[F_c]_o$ acts through point "N" and is normal (outward) to the plane of the figure. $[M_{cb}]_o$ is now resolved into components of the ℓ-n axes system as follows:

$$[M_{cb}]_{no} = [C_F]_o \cos\zeta(x_o)\{p_o \sin\beta_o + q_o \cos\beta_o + Y_{co}\} \tag{6.13}$$

$$[M_{cb}]_{\ell o} = [C_F]_o \cos\zeta(x_o)\{q_o \sin\beta_o - p_o \cos\beta_o + X_{co}\} \tag{6.14}$$

where:

β_o = pitch angle of the blade section at $x = x_o = r_o/R$;

X_{co} = distance of the blade sections centroid from the generator line (ft);

Y_{co} = distance of the blade section's centroid from the pitch reference line (ft);

q_o = distance to point "N" from point "P" parallel to the shaft axis at $x = x_o = r_o/R$ (ft);

p_o = distance to point "N" from point "P" perpendicular to the shaft axis at $x = x_o = r_o/R$ (ft).

The quantity β_o is found by the relation:

$$\tan\beta_o = \frac{1}{\pi} \cdot (P/D)_o \tag{6.15}$$

For the Wageningen B-Screw Series, $(P/D)_o$ is a constant along R except for propellers with Z = 4.

The quantity $[C_F]_o$ is computed from the relation:

$$[C_F]_o = 1728 \cdot \frac{wd\, V_o}{acg} \cdot (2\pi n_p)^2 \cdot R \cdot (\bar{x}_G)_o \tag{6.16}$$

where:

V_o = volume of the blade element above the blade section at $x = x_o = r_o/R$ (ft^3);

acg = 32.174 ft/sec^2;

wd = material weight density (lbf/in^3);

n_P = propeller revolution rate (rps);

$(\bar{x}_G)_o$ = non-dimensional radial position of "G" for the blade element above the shaft axis;

R = propeller radius (ft).

At this point, only five quantities remain to be determined for the evaluation of the expressions of equations (6.10), (6.13) and (6.14). They are:

1) $\cos \zeta(x_o)$
2) p_o
3) q_o
4) $(\bar{x}_G)_o$
5) V_o

These quantities are determined by integration over the blade element above the blade section, located at $x = x_o = r_o/R$, from $x = x_o$ to $x = 1.0$.

The values for p_o and q_o will vary with the location of "G" (from Figure (6.3)) which depends on x. Consider a radially thin slice of the blade element above the blade section, located at $x = x_o = r_o/R$ (see Figure (6.5)). This thin "slice" is located at a non-dimensional distance x from the shaft centerline where $x_o < x < 1.0$. Figure (6.6) depicts this section expanded onto a plane. Let "g" be the centroid of that "slice". If x_g is the distance from the generator

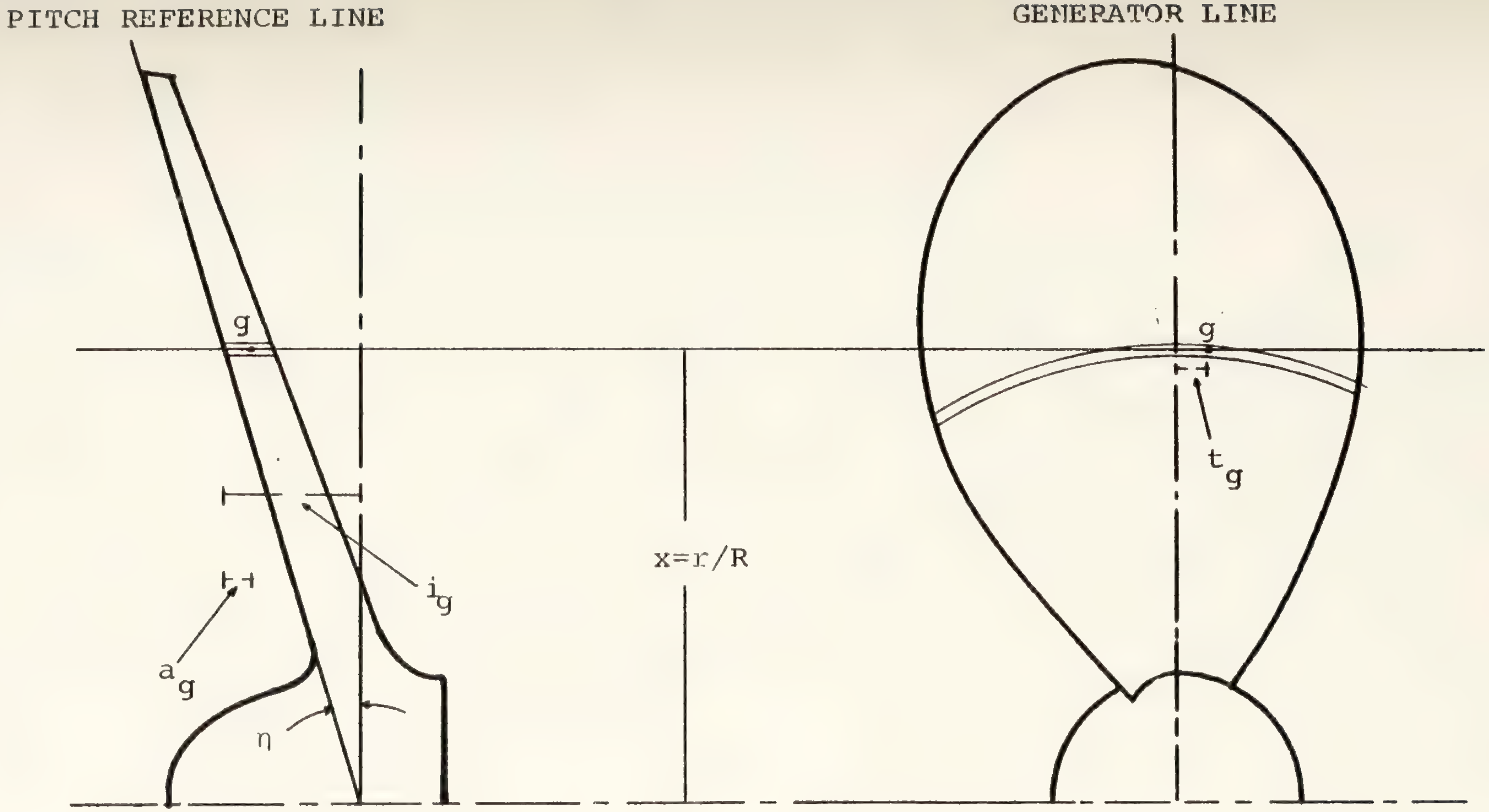

Figure 6.5   Position of "g" of a Blade Section "Slice" at x = r/R

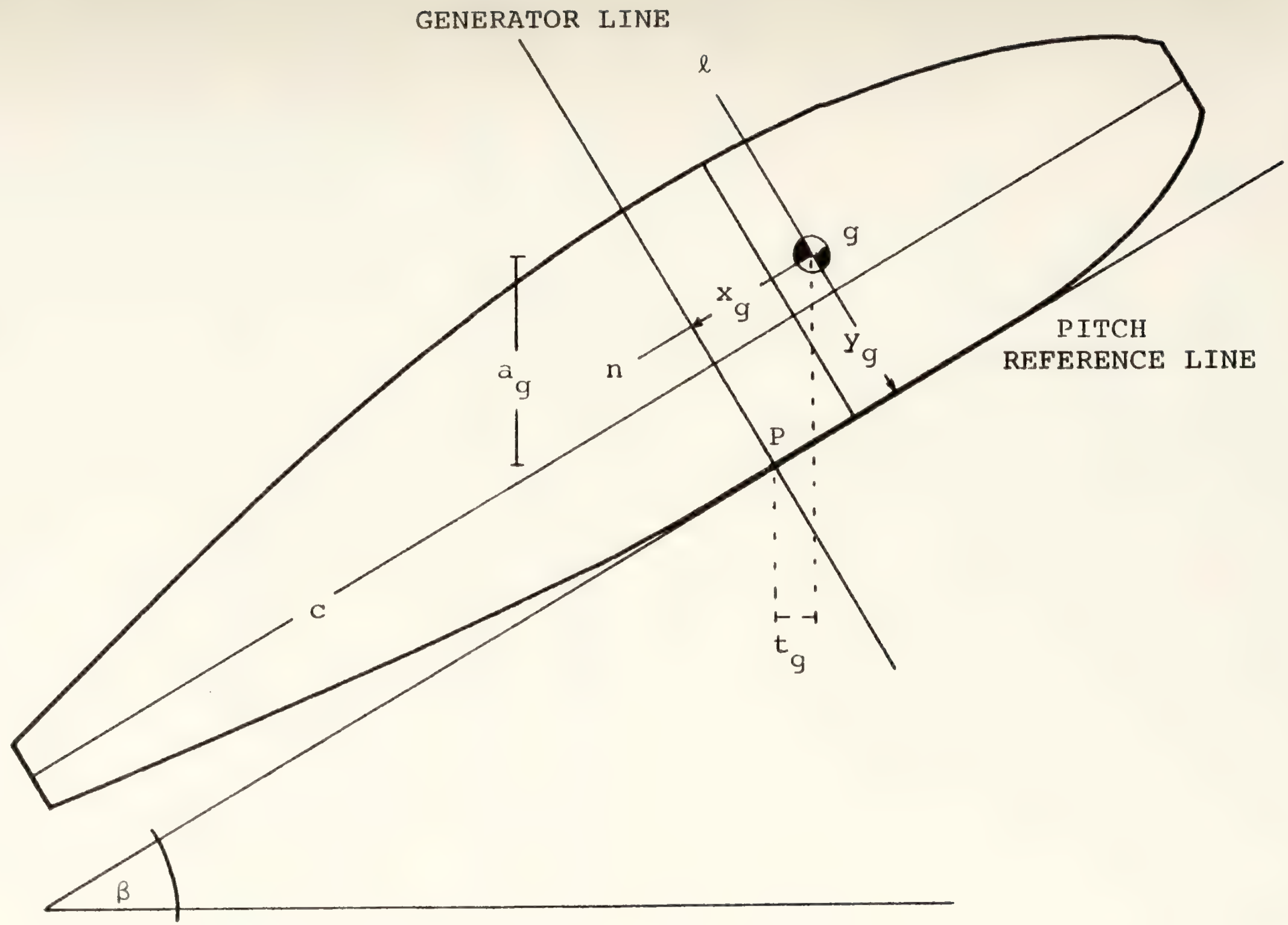

Figure 6.6 Coordinates of centroid "G" of any Blade Section

line to "g" in feet and y_g is the distance from the pitch reference line in feet, then, from Figures (6.5) and (6.6), the following relations apply:

$$i_g = x R \tan \eta \tag{6.17}$$

$$i_g - a_g = i_g - x_g \sin \beta_g - y_g \cos \beta_g \tag{6.18}$$

$$t_g = x_g \cos \beta_g - y_g \sin \beta_g \tag{6.19}$$

where:

η = rake angle at x;

x_g = distance of "g" from point "P" parallel to the shaft axis (ft);

y_g = distance of "g" from point "P" perpendicular to the shaft axis (ft).

For the Wageningen B-Screw Series, rake angle η is a constant 15° everywhere along the radius R.

Now, to compute the volume of the blade element above the blade section located at $x = x_o = r_o/R$, the following expression is used:

$$V_o = \int_{x=x_o}^{1} RA(x)\ dx \tag{6.20}$$

To compute the non-dimensional radial position of "G" for the blade element above a blade section located at $x = x_o = r_o/R$, the following expression is used:

$$(\bar{x}_G)_o = \frac{\int_{x=x_o}^{1} A(x)\, x\, dx}{\int_{x=x_o}^{1} A(x)\, dx} \tag{6.21}$$

To compute the tangential position of "G" for the blade element above a blade section located at $x = x_o = r_o/R$, the following expression is used:

$$T_o = \frac{\int_{x=x_o}^{1} A(x)\, t_g\, dx}{\int_{x=x_o}^{1} A(x)\, dx} \tag{6.22}$$

And, finally, to compute the axial position of "G" for the blade element above a blade section located at $x = x_o = r_o/R$, the following expression is used:

$$A_o = \frac{\int_{x_o}^{1} A(x)\,(i_g - a_g)\, dx}{\int_{x_o}^{1} A(x)\, dx} \tag{6.23}$$

Using the values just determined for $(\bar{x}_G)_o$, T_o and A_o, the following expressions are used to evaluate p_o and q_o:

$$p_o = \frac{x_o}{(\bar{x}_G)_o}\, T_o \tag{6.24}$$

$$q_o = A_o - x_o \tan \eta \qquad (6.25)$$

The expression for $\cos \zeta(x_o)$ follows:

$$\cos \zeta(x_o) = \frac{p_o}{x_o R} \qquad (6.26)$$

The formulation is now complete. Equations (6.10), (6.13) and (6.14) can now be evaluated for any blade section located at $x = x_o = r_o/R$. From here, equations (6.2) and (6.3) are evaluated. Finally, using the results from these equations and equation (6.9), equation (6.1) can be evaluated for the four points, specified by coordinates (u1,w1), (u2,w2), (u3,w3) and (u4,w4), at any location $x = x_o = r_o/R$.

From the development discussed in Chapter V, the values for $A(x)$, x_g, y_g, I_{no} and $I_{\ell o}$ are readily available.

D. ALGORITHM FOR THE CONSTRAINT

1. Theory

Schoenherr's formulation with the modifications just derived can be used in determining the minimum required equivalent blade section maximum thickness-to-chord ratio ($(t^*/c)_{.75R\ min}$) for use in the constraint $G_{11}(\bar{X}) \leq 0$ given by equation (4.8). The procedure employed is as follows:

1) assume an initial value for $(t^*/c)_{.75R\ min}$ using equation (3.21);

2) increase this value by a small amount;

3) using $(t^*/c)_{.75R\ min}$ obtained from step (2), generate a distribution of minimum required blade section thicknesses (t^*_{min}) for blade sections at specified points along the propeller radius, say at r = .2R, .3R, .4R, .5R, .6R, .7R, .8R and .9R;

4) determine all blade section properties to include: a) cross-sectional area, b) chord length, c) centroid location, d) moments of inertia with respect to the principal axes system (i.e., ℓ-n system), e) coordinate values for the four critical points defined in the previous section;

5) compute the hydrodynamic bending moment components $[M_P]_{no}$ and $[M_P]_{\ell o}$ at radius locations just specified;

6) compute the values of the centrifugal force $[F_c]_o$ and the bending moment components $[M_{cb}]_{no}$ and $[M_{cb}]_{\ell o}$ acting on blade sections at radius locations just specified;

7) calculate the direct fiber stresses at all four critical points for all radius locations specified in step (3);

8) check the following condition on the calculated fiber stress at all four critical points at all specified radius locations using:

$$[\sigma]_o \leq 144 \cdot S_c \tag{6.27}$$

9) if the maximum allowable stress (S_c) for the material is exceeded, then return to step (2) and repeat. Otherwise, proceed to next step.

10) since the minimum required equivalent blade section maximum thickness-to-chord ratio assumed in step (2) has produced blade sections of adequate strength, evaluate the constraint given by equation (4.8).

2. Coding Details

The algorithm just outlined is incorporated into the main FORTRAN subprogram SUBROUTINE STRCNK. This subprogram, in turn, executes the algorithm through sequential calls to other key FORTRAN subprograms. These subprograms are listed as follows:

1) SUBROUTINE TDIST--accomplishes step (3); generates, at specified radius values, a distribution of minimum required blade section maximum thicknesses (t^*_{min}) for the assumed value of $(t^*/c)_{.75R\ min}$;

2) SUBROUTINE BLDPRP--accomplishes step (4); described previously in Chapter V;

3) SUBROUTINE HYDLD--accomplishes step (5); computes the hydrodynamic bending moment components, given by equations (6.6) and (6.7), at specified radius locations;

4) SUBROUTINE CNFGLD--accomplishes step (6); computes the centrifugal force and bending moments, given by equations (6.9), (6.13) and (6.14) respectively, at specified radius locations;

5) SUBROUTINE SIGNDS--accomplishes step (7); computes direct fiber stresses, given by equation (6.1), for all four critical points at every specified radius location.

During the remaining steps of SUBROUTINE STRCNK, the condition on allowable stress, given by equation (6.27), is checked at all critical points of blade sections located at specified radius locations (again, r = .2R, .3R, .4R, .5R, .6R, .7R, .8R and .9R). The final calculation made is that for the constraint given by equation (4.8).

Again, extensive use of common blocks, for passing data from one subprogram to another, is apparent upon examination of the codes just cited. Comment cards are used throughout.

E. SUMMARY

The end of this chapter marks the completion of all prerequisite background and formulation discussions on the application of COPES/CONMIN to propeller selection problems involving the Wageningen B-Screw Series. From this point, each specific Design Case can now be solved as an optimization problem.

VII. DESIGN CASE NO. 1--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of propeller selection problems which use the "thrust" approach. First, the thrust approach to the propeller selection problem is formulated. Then, a review of a previous author's solution to this problem is presented. Four variations to this propeller selection problem are solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results from the four variations.

B. THRUST APPROACH FORMULATION

1. Design Vector $\overline{X1}$

As previously pointed out at the conclusion of Chapter III, Design Case No. 1 constitutes a propeller selection problem which is solved by the thrust approach. In this approach, the effective horsepower (P_E) and the ship's speed (V) are specified by the designer. From the viewpoint of optimization, the quantities P_E and V become preassigned parameters. This reduces the design vector $\overline{X}$ (see Figure 4.1) to:

$$\overline{X} = \left\{ \begin{array}{l} D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \\ N_P \\ Q_S \end{array} \right\} \tag{7.1}$$

Having specified P_E and V, all of the design variables, as listed in equation (7.1), are not independent. Recalling equations (3.3) and (3.13), the following relationship results:

$$P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \cdot \eta_o \cdot \frac{2\pi Q_S}{550} \cdot \frac{N_P}{60} \tag{7.2}$$

Rearranging terms, this equation becomes:

$$\eta_o \; Q_S \; N_P = \frac{(1-wt)}{(1-td)} \cdot \frac{P_E}{\eta_R} \cdot \frac{550 \cdot 60}{2\pi} \tag{7.3}$$

Considering that the open water efficiency (η_o) is evaluated prior to the computation of ($-\eta_o$), or $OBJ_{1,2}$, then both N_P and Q_S are not independent design variables. One must be selected as the independent design variable. Then, the other variable becomes dependent on the one just selected.

For this study, N_P is selected as the independent design variable. This choice will reduce the design vector $\bar{X}$ for propeller selection problems using the thrust approach to the following:

$$\bar{X} = \left\{ \begin{array}{l} D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \\ N_P \end{array} \right\} \tag{7.4}$$

Finally, equation (3.8) implies an alternative definition of $\overline{X}$ as given in equation (7.4). The design vector for Design Case No. 1 propeller selection problems is, therefore, defined as:

$$\overline{X1} = \left\{ \begin{matrix} D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \\ J \end{matrix} \right\} \qquad (7.5)$$

2. <u>Powering Constraint</u>

Having determined the design vector $\overline{X1}$, a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint $G_{12}(\overline{X})$ mentioned in Chapter IV.

Simply stated, the selected propeller, as defined by $\overline{X1}$, must <u>develop</u> enough thrust (T) so that the powering requirement, specified by P_E and V, is met. Using equation (3.2), the thrust developed by the propeller can be specified in terms of thrust horsepower (P_T) as:

$$(P_T)_{dev} = \frac{T\ V(1\text{-}wt)}{550} \qquad (7.6)$$

From equation (3.9), it follows that:

$$(P_T)_{dev} = \frac{\rho\ n_P^2\ D^4\ K_T}{550} \cdot V(1\text{-}wt) \qquad (7.7)$$

Using equation (3.12), the developed thrust horsepower can be defined in terms of developed effective horsepower given by:

$$(P_E)_{dev} = \frac{(1-td)}{(1-wt)} \cdot (P_T)_{dev} \qquad (7.8)$$

The restriction imposed by the thrust approach method, where P_E and V are specified, can now be stated as:

$$P_E \leq (P_E)_{dev} \qquad (7.9)$$

Rearranging equation (7.9), the constraint $G_{12}(\overline{X1})$ follows:

$$G_{12}(\overline{X1}) = 1 - \frac{(P_E)_{dev}}{P_E} \leq 0 \qquad (7.10)$$

With the design vector $\overline{X1}$ and $G_{12}(\overline{X1})$ defined, the propeller selection problem represented by Design Case No. 1 can be stated under one equation as:

$$\begin{aligned} &\text{Maximize:} && F(\overline{X1}) = OBJ_{1,2} \\ &\text{Subject to:} && G_j(\overline{X1}) \leq 0 \qquad j = 1,\ldots,12 \qquad (7.11) \\ & && X1_i^{lower} \leq X1_i \leq X1_i^{upper} \qquad i = 1,\ldots,5 \end{aligned}$$

C. PREVIOUS SOLUTIONS

Triantafyllou [Refs. 3,21] considered a propeller selection problem represented by Design Case No. 1. In his example problem, the following parameters were specified:

1) $\nu = 1.139 \times 10^{-6}$ (m^2/sec) $= 1.22613 \times 10^{-5}$ (ft^2/sec)

2) wt = .22

3) td = .19

4) $\eta_R = 1.025$

5) noscrw = 1

6) Z = 5

7) P_E = 18153 (hp)

8) V = 24 (knots)

9) D = 22.0 (ft)

10) A_E/A_O = .85

The hull under study in his example had the following dimensions:

1) Length = 710 (ft)

2) Draft = 30 (ft)

3) Beam = 100 (ft)

For his analysis, the design vector contained two variables and was specified as:

$$\overline{XT} = \left\{ \begin{array}{c} J \\ \\ P/D \end{array} \right\}$$

Using an iterative scheme [Ref. 21: p. 79] to solve two equations in two unknowns, he maximized the open water efficiency (η_o) to obtain the following results:

$$P/D = 1.1651$$

$$N_P = 104 \text{ (rpm)}$$

$$P_D = 25544 \text{ (hp)}$$

$$\eta_o = .6676$$

For future comparisons, equations (3.8) and (3.3) give:

$$J = .8286$$

$$Q_S = 1290000.0 \text{ (ft-lbf)}$$

Triantafyllou's results are summarized in Table (IV).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (7.11), is now solved by COPES/CONMIN. Four solution variations are considered.

The first and second variations attempt to reproduce the solution given by Triantafyllou. The design vector $\overline{XT}$ (NDV = 2) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint $G_{12}(\overline{XT})$ given by equation (4.8). The other uses SUBROUTINE STRCNK to determine $G_{12}(\overline{XT})$.

The remaining two variations will solve the propeller selection problem using the design vector $\overline{XI}$ (NDV = 5) defined in equation (7.5). Again, one variation uses SUBROUTINE STRCNA; the other, SUBROUTINE STRCNK.

In all variations, the following parameters are used:

1) Temp = 59 (°F)
2) $\rho = 1.9384$ (lbf-sec^2/ft^4)
3) $\nu = 1.2285 \ 10$ (ft^2/sec)

4) $p_{watvap} = .247$ (psia)

5) $p_{atm} = 14.7$ (psia)

6) wt = .22

7) td = .19

8) $\eta_R = 1.025$

9) noscrw = 1

10) $h_{c\ell} = 19.0$ (ft)

11) $D_{lim} = 22.0$ (ft)

12) Z = 5

13) promat = 5 (stainless steel; see Table (II))

14) $P_E = 18153$ (hp)

15) V = 24.0 (knots)

All of the above are initialized in the input phase (ICALC = 1) of each SUBROUTINE ANALIZ pertaining to each variation.

The constraint $G_{12}(\overline{XI})$ or $G_{12}(\overline{XT})$ is evaluated by SUBROUTINE BLPOW1 which appears in the execution section of each SUBROUTINE ANALIZ.

1. Variation 1

a. Programming Details

Since this variation uses the design vector $\overline{XT}$, the following design variables of $\overline{XI}$ become parameters and are specified in the input section of SUBROUTINE ANALIZ (ICALC = 1) as:

1) D = 22.0 (ft)

2) $A_E/A_O = .85$

3) $(t^*/c)_{.75R} = .0348$ (from equation 3.21).

For constraints, the following are used:

$$G_j(\overline{XT}) \leq 0 \qquad j = 1,\ldots,8,\ 12$$

Only nine of twelve constraints are evaluated (NCON = 9). Obviously, some of the twelve constraints are redundant since D, A_E/A_O, and $(t^*/c)_{.75R}$ have been specified.

The upper (XT_i^{upper}) and lower (XT_i^{lower}) limits on the design variables J and P/D are set to be:

$$.01 \leq J \leq 1.6$$

$$.4 \leq P/D \leq 1.4$$

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable (XT_i) is also assigned on card image F under the field labeled X. The first list of card images in Appendix D lists all of the COPES control cards used for this variation and variation 2. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed first in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

2. Variation 2

a. Programming Details

Everything discussed above for the first variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the second variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNK.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed second in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

3. Variation 3

a. Programming Details

This variation uses the design vector $\overline{X1}$. For constraints, the following are used:

$$G_j(\overline{X1}) \leq 0 \quad j = 1,\ldots,12$$

All twelve constraints are evaluated (NCON = 12).

The upper ($X1_i^{upper}$) and lower ($X1_i^{lower}$) limits on the design variables D, P/D, A_E/A_O, $(t^*/c)_{.75R}$, and J are set as:

$$1.0 \leq D \leq 50.0 \quad \text{(ft)}$$

$$.4 \leq P/D \leq 1.4$$

$$.2 \leq A_E/A_O \leq 1.1$$

$$.003 \leq (t^*/c)_{.75R} \leq .50$$

$$.01 \leq J \leq 1.6$$

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable (Xl_i) is also assigned on card image F under the field labeled X. The second list of card images in Appendix D lists all of the COPES control cards used for this variation and variation 4. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed third in Appendix E. Results for this variation of thepropeller selection problem are tabulated in Table (IV).

4. <u>Variation 4</u>

a. Programming Details

Everything discussed above for the third variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the fourth variation, found in Appendix C, shows the calling statement made to SUBROUTINE STRCNK instead of SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed last in Appendix E. Results for this variation of the propeller selection problem are tabulated in Table (IV).

E. DISCUSSION

Overall, the results achieved in all variations compare reasonably well to the solution obtained by Triantafyllou. However, the following points can be made.

Variations 1 and 2 give the same results. This was expected in view of the fact that, even though constraints $G_9(\overline{XT})$ through $G_{11}(\overline{XT})$ were evaluated, these constraints were not considered in the optimization search conducted by CONMIN.

In variations 3 and 4, the diameter (D) was driven to the limit (D_{lim}). This bears out a fundamental rule in propeller design, i.e., the larger the propeller diameter (D), the greater the open water efficiency (η_o).

The minimum required equivalent blade section maximum thickness-to-chord ratio ($(t^*/c)_{.75R\,min}$), computed in

variation 3, is substantially smaller than the one computed for variation 4. As pointed out in Reference [2], the empirical relation, expressed by equation (4.9) and derived from equation (70.x) [Ref. 46: p. 620], does not take into account the effects of centrifugal loading. These effects include, specifically, the direct stresses imposed by the inertia load of the blade and the bending moments which result from rake and skew of the blade. Therefore, the algorithm developed in Chapter VI should, and does, produce a larger value for $(t^*/c)_{.75R}$.

A final observation on the results concerns the values of the open water efficiency. The "optimum" open water efficiency (η_o) achieved by Triantafyllou is lower than those achieved in variations 1 and 2. A possible reason for this might be the neglection of the term "dRe/dJ" in Triantafyllou's formulation of the analytical expressions [Ref. 21: p. 71] that he used in his analysis. The difference in the open water efficiencies subsequently accounts for the differences in the propeller revolution rate (N_p) and the delivered torque (Q_S) when the relation in equation (3.3) is considered.

TABLE IV

Design Case No. 1--Results

GROUP	ITEM	TRIANTA-FYLLOU	1	2	3	4
Given	P_E	18153.0	18153.0	18153.0	18153.0	18153.0
	V	24.0	24.0	24.0	24.0	24.0
Design Variable Speci-fied	D	22.0	22.0	22.0		
	A_E/A_O	.85	.85	.85		
	$(t^*/c)_{.75R}$		.0348	.0348		
Design Variables	D				21.9991	21.9659
	P/D	1.1651	1.0036	1.0036	.9981	1.0071
	A_E/A_O				.8205	.8149
	$(t^*/c)_{.75R}$				.0330	.0642
	J	.8286	.7371	.7371	.7343	.7394
Maximize	η_O	.6676	.7091	.7091	.7109	.7066
Restric-tions	D_{lim}		(22.0)	(22.0)	22.0	22.0
	$A_E/A_{O\,min}$		(0.5258)	(0.5258)	.5269	.5267
	$(t^*/c)_{.75Rmin}$		(0.21266)	(0.50761)	.021998	.053259
Other	N_P	104	116.9	116.9	117.4	116.7
	Q_S	1290000	1080451.	1080451	1064574	1084003
	P_D	25544.0	24051.3	24051.3	24030.3	24094.8

VIII. DESIGN CASE NO. 2--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of propeller selection problems which use the "power" approach. First, the power approach to the propeller selection problem is formulated. Then, a review of a previous author's solution to this problem is presented. Four variations to this propeller selection problem are solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results from the four variations.

B. POWER APPROACH FORMULATION

1. Design Vector $\overline{X2}$

As previously pointed out at the conclusion of Chapter III, Design Case No. 2 constitutes a propeller selection problem which is solved by the power approach. In this approach, the delivered torque (Q_S) and the propeller revolution rate (N_P) are specified by the designer. From the viewpoint of optimization, the quantities Q_S and N_P become preassigned parameters. This reduces the design vector $\overline{X}$ (see Figure (4.1)) to:

$$\overline{X} = \left\{ \begin{array}{l} P_E \\ V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{array} \right\} \qquad (8.1)$$

Having specified Q_S and N_P, all of the design variables, as listed in equation (8.1), are not independent. Recalling equations (3.3), (3.11) and (3.13), the following relationship results:

$$P_E = \frac{(1-td)}{(1-wt)} \cdot \eta_R \cdot \frac{J\,K_T}{2\pi K_Q} \cdot \frac{2\pi Q_S}{550} \cdot \frac{N_P}{60} \tag{8.2}$$

Rearranging terms, this equation becomes:

$$\frac{P_E}{V} = \frac{(1-td)}{(1-wt)} \cdot \eta_R \cdot \frac{(1-wt)}{n_P\,D} \cdot \frac{K_T}{K_Q} \cdot \frac{Q_S}{550} \cdot \frac{N_P}{60} \tag{8.3}$$

Considering the relations for K_T and K_Q in equation (3.17), then both P_E and V are not independent design variables. One must be selected as independent, while the other becomes dependent on the one selected.

For this study, V is selected as the independent design variable. This choice will reduce the design vector $\overline{X}$ for propeller selection problems using the power approach to the following:

$$\overline{X} = \begin{Bmatrix} V \\ D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{Bmatrix} \tag{8.4}$$

Finally, equation (3.8) implies an alternative definition of $\overline{X}$ as given in equation (8.4). The design vector for

Design Case No. 2 propeller selection problems is, therefore, defined as:

$$\overline{X2} = \begin{Bmatrix} V \\ J \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{Bmatrix} \tag{8.5}$$

2. <u>Powering Constraint</u>

Having determined the design vector $\overline{X2}$, a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint $G_{12}(\overline{X})$ mentioned in Chapter IV.

Simply stated, the selected propeller, as defined by X2, must <u>absorb</u> at least all of the power delivered to it (P_D) which is specified in terms of Q_S and N_P. Using equation (3.3), the power absorbed by the propeller can be specified in terms of delivered horsepower (P_D) as:

$$(P_D)_{absorb} = \frac{2\pi \; Q_P}{550} \cdot \frac{N_P}{60} \tag{8.6}$$

From equation (3.10), it follows that:

$$(P_D)_{absorb} = \frac{K_Q \; \rho \; n_P^2 \; D^5}{550} \cdot \frac{2\pi \; N_P}{60} \tag{8.7}$$

But, equation (3.3) also defines the power <u>delivered</u> to the propeller as:

$$P_D = \frac{2\pi\ Q_S}{550} \cdot \frac{N_P}{60} \qquad (8.8)$$

The restriction imposed by the power approach method, where Q_S and N_P are specified, can now be stated as:

$$P_D \leq (P_D)_{absorb} \qquad (8.9)$$

Rearranging equation (8.9), the constraint $G_{12}(\overline{X2})$ follows:

$$G_{12}(\overline{X2}) = 1 - \frac{(P_D)_{absorb}}{P_D} \leq 0 \qquad (8.10)$$

Further simplification of equation (8.10) gives:

$$G_{12}(\overline{X2}) = 1 - \frac{Q_P}{Q_S} \leq 0 \qquad (8.11)$$

With the design vector $\overline{X2}$ and $G_{12}(\overline{X2})$ defined, the propeller selection problem represented by Design Case No. 2 can be stated under one equation as:

$$\begin{aligned} &\text{Minimize:} \quad F(\overline{X2}) = OBJ_{1,2} \\ &\text{Subject to:} \quad G_j(\overline{X2}) \leq 0 \quad j = 1,\ldots,12 \\ &\qquad X2_i^{lower} \leq X2_i \leq X2_i^{upper} \quad i = 1,\ldots,5 \end{aligned} \qquad (8.12)$$

C. PREVIOUS SOLUTIONS

Markussen [Ref. 4] considered a propeller selection problem represented by Design Case No. 2. In his example problem,

the following parameters were specified:

1) Temp = 18 (°C) = 64.4 (°F)

2) P_{watvap} = 0.0206411 (bars) = .29943921 (psia)

3) P_{atm} = 1.01312856 (bars) = 14.6974 (psia)

4) noscrw = 1

5) $h_{c\ell}$ = 6.7 (meters) = 21.9827 (ft)

6) Z = 6

7) P_D = 18.9 (MegaWatts) = 25344.9 (hp)

8) N_P = 110 (rpm)

9) V_A = 15.65 (knots)

For his analysis, the design vector contained three variables and was specified as:

$$\overline{XM} = \left\{ \begin{array}{c} J \\ P/D \\ A_E/A_O \end{array} \right\}$$

A restriction for the minimum required expanded area ratio ($(A_E/A_O)_{min}$), given by equation (4.3), was also considered. This imposed a constraint given by equation (4.4).

Using an iterative scheme [Ref. 4: p. 110] to solve three equations in three unknowns, Markussen maximized the open water efficiency (η_o) to obtain the following results:

$$J = .61095$$

$$P/D = .864380$$

$$A_E/A_O = 36.1861/40.6123 \ (m^2/m^2)$$

$$= .891012$$

$$\eta_o = .654391$$

For future comparisons, equations (3.8) and (3.3) give:

$$D = 7.19091 \text{ (meters)} = 23.593375 \text{ (ft)}$$

$$Q_S = 1210130.0 \text{ (ft-lbf)}$$

Markussen's results are summarized in Table (V).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (8.12), is now solved by COPES/CONMIN. Four solution variations are considered.

The first and second variations attempt to reproduce the solution given by Markussen. The design vector $\overline{XM}$ (NDV = 3) is used in both cases. One variation uses SUBROUTINE STRCNA to evaluate the constraint $G_{12}(\overline{XM})$ given by equation (4.8). The other uses SUBROUTINE STRCNK to determine $G_{12}(\overline{XM})$.

The remaining two variations will solve the propeller selection problem using the design vector $\overline{X2}$ (NDV = 5) defined in equation (8.5). Again, one variation uses SUBROUTINE STRCNA; the other, SUBROUTINE STRCNK.

In all variations, the following parameters are used:

1) Temp = 64.4 (°F)
2) $\rho = 1.9892$ (lbf-sec^2/ft^4)
3) $\nu = 1.1900 \times 10^{-5}$ (ft^2/sec)
4) $p_{watvap} = .2994$ (psia)

5) p_{atm} = 14.697 (psia)

6) wt = .22

7) td = .19

8) η_R = 1.025

9) noscrw = 1

10) $h_{c\ell}$ = 21.9827 (ft)

11) D_{lim} = 30.0 (ft)

12) Z = 6

13) promat = 5 (stainless steel; see Table (II))

14) Q_S = 1210130 (ft-lbf)

15) N_P = 110 (rpm)

All of the above are initialized in the input phase (ICALC = 1) of each SUBROUTINE ANALIZ pertaining to each variation.

The constraint $G_{12}(\overline{X2})$ or $G_{12}(\overline{XM})$ is evaluated by SUBROUTINE BLPOW2 which appears in the execution section of each SUBROUTINE ANALIZ.

1. Variation 1

a. Programming Details

Since this variation uses the design vector $\overline{XM}$, the following design variables of $\overline{X2}$ become parameters and are specified in the input section of SUBROUTINE ANALIZ (ICALC = 1). The ship's speed (V) is specified as:

$$V = V_A/(1-wt)$$
$$= 15.65/(1 - .22)$$
$$= 20.0641 \quad \text{(knots)}$$

Markussen elected to use the standard Wageningen blade section maximum thickness-to-chord ratios. Since the equivalent t/c is given as a function of Z and A_E/A_O (see equation (3.21)), then $(t^*/c)_{.75R}$ is calculated during each analysis (ICALC = 2) by the following relation:

$$(t^*/c)_{.75R} = (t/c)_{.75R}$$

For constraints, the following are used:

$$G_j(\overline{XT}) \leq 0 \qquad j = 1,\ldots,8,\ 10,\ 12$$

Only ten of twelve constraints are considered (NCON = 10). Constraints $G_9(\overline{XM})$ and $G_{11}(\overline{XM})$ are redundant since no limit on the propeller diameter (D_{lim}) appears as a parameter in Markussen's formulation and $(t^*/c)_{.75R}$ was taken to be the Wageningen standard.

The upper (XM_i^{upper}) and lower (XM_i^{lower}) limits on the design variables J, P/D and A_E/A_O are set to be:

$$.01 \leq J \leq 1.1$$

$$.4 \leq P/D \leq 1.4$$

$$.4 \leq A_E/A_O \leq 1.1$$

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VIB. The initial value for each design variable (XM_i) is

also assigned on card image F under the field labeled X. The first list of card images in Appendix G lists all of the COPES control cards used for this variation and variation 2. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed first in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

2. Variation 2

a. Programming Details

Everything discussed above for the first variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the second variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNK instead of SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed second in Appendix H.

Results for this variation of the propeller selection problem are tabulated in Table (V).

3. Variation 3

a. Programming Details

This variation uses the design vector $\overline{X2}$. For constraints, the following are used:

$$G_j(\overline{X2}) \leq 0 \qquad j = 1,\ldots,12$$

All twelve constraints are evaluated (NCON = 12).

The upper ($X2_i^{upper}$) and lower ($X2_i^{lower}$) limits on the design variables V, P/D, A_E/A_O, $(t^*/c)_{.75R}$, and J are set as:

$$10.0 \leq V \leq 100.0 \quad \text{(ft/sec)}$$

$$.4 \leq P/D \leq 1.4$$

$$.4 \leq A_E/A_O \leq 1.1$$

$$.003 \leq (t^*/c)_{.75R} \leq .50$$

$$.01 \leq J \leq 1.1$$

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable ($X2_i$) is also assigned on card image F under the field labeled X. The second list of card images in Appendix G lists all of the COPES control cards used for this variation and variation 4. These cards also specify the locations of the design variables

in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

An examination of SUBROUTINE ANALIZ for this variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed third in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

4. Variation 4

a. Programming Details

Everything discussed above for the third variation applies here with one exception. An examination of SUBROUTINE ANALIZ for the fourth variation, found in Appendix F, shows the calling statement made to SUBROUTINE STRCNK instead of SUBROUTINE STRCNA.

b. Results

The output from the optimization/analysis, performed by COPES/CONMIN, is listed last in Appendix H. Results for this variation of the propeller selection problem are tabulated in Table (V).

E. DISCUSSION

The results achieved in variations 1 and 2 compare extremely well to the solution obtained by Markussen. As

pointed out in the discussion in Chapter VII, variations 1 and 2 are expected to give the same results for the vector $\overline{XM}$. Obviously, the values obtained for J and P/D, as well as those for D, and $Rn^*_{.75R}$, are very close to the values generated in Markussen's example. However, the values for A_E/A_O are somewhat different. It is interesting to note that the value obtained in variations 1 and 2 (and, for that matter, variations 3 and 4) is, essentially, the limiting value for A_E/A_O, as given in Table (I), for Z = 6. Markussen's value for A_E/A_O (i.e., .891012) exceeds the limit (i.e., .80) in this table.

As pointed out at the end of Chapter VII, the minimum required blade section maximum thickness-to-chord ratio ($(t^*/c)_{.75R\,min}$), computed in variations 1 and 3, is substantially smaller than the one computed for variations 2 and 4. Again, the same explanation applies here as well.

The results of variations 3 and 4 differ somewhat from Markussen's results. The reason for this is simply that V_A (or V) has not been specified as a parameter. Consequently, a higher value for the advance ratio (J), which corresponds to a higher open water efficiency (η_O), has been found in the optimization search. This result can be interpreted in the following way. Given:

1) a six-bladed Wageningen propeller (Z = 6) which is made out of stainless steel (promat = 5);

2) a power train delivering 25344.9 (hp) at a rate of 110 (rpm);

3) a hull with a wake fraction (wt) equal to .22, a thrust deduction (td) equal to .19 and a shaft centerline depth ($h_{c\ell}$) of 21.98 (ft),

then, the selected propeller, as defined by $\overline{X2}$, can drive this hull at a maximum speed of V when the hull has a maximum resistance given by P_E.

TABLE V

Design Case No. 2--Results

GROUP	ITEM	MARKUSSEN	VARIATIONS 1	2	3	4
Given	P_D	25344.9	25344.9	25344.9	25344.9	25344.9
	Q_S	1210130	1210130	1210130	1210130	1210130
	N_P	110	110	110	110	110
Design Variable Specified	V_A	15.65	15.65	15.65		
	V		20.0641	20.0641		
Design Variables	J	.61095	.6475	.6475	.9927	.8753
	V				30.9138	29.5355
	V_A				24.1127	23.0377
	P/D	.864380	.9036	.9036	1.1986	1.0308
	A_E/A_O	.891012	.8018	.8018	.7946	.7986
	$(t^*/c)_{.75R}$		.0397	.0397	.0499	.0638
Maximize	η_O	.654391	.6660	.6660	.7643	.7330
Restrictions	D_{lim}		(30.0)	(30.0)	30.0	30.0
	$A_E/A_{O\,min}$	.574729	.5070	.5070	.4622	.4266
	$(t^*/c)_{.75Rmin}$		(.02729)	(.0647)	.02706	.0638
Other	D	23.53	22.25	22.25	22.36	24.23
	P_E		(14057.3)	(14057.3)	19945.5	20653.7
	$Rn^*_{.75R}$	6.478×10^7	5×10^7	5×10^7	5×10^7	5×10^7

IX. DESIGN CASE NO. 3--PROGRAMMING AND COMPARISONS

A. INTRODUCTION

In this chapter, COPES/CONMIN is used in the solution of a propeller selection problem where "matching" is desired. First, the "matching" approach to the propeller selection problem is formulated. Then, a review of a previous author's solution is presented. One variation to this propeller selection problem is solved by COPES/CONMIN. The chapter is completed with a presentation and discussion of the results.

B. "MATCHING" FORMULATION

1. Design Vector $\overline{X3}$

Design Case No. 3, the final powering problem considered in this study, constitutes a propeller selection problem solved by the "matching" approach. In this approach, the hull's effective horsepower (P_E) and speed (V), the delivered torque (Q_S) and the propeller revolution rate (N_P) are specified by the designer. This reduces the design vector $\overline{X}$ (see Figure (4.1)) to:

$$\overline{X} = \left\{ \begin{array}{l} D \\ P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{array} \right\} \tag{9.1}$$

For this study, the design vector $\overline{X}$ is reduced further by eliminating the propeller diameter (D) as a design variable.

That is, D will also be specified by the designer so that the design vector for Design Case No. 3 is defined as:

$$\overline{X3} = \begin{Bmatrix} P/D \\ A_E/A_O \\ (t^*/c)_{.75R} \end{Bmatrix} \tag{9.2}$$

2. Powering Constraint(s)

Having determined the design vector $\overline{X3}$, a final restriction to the general propeller selection problem, as stated by equation (4.24), remains for consideration. This restriction constitutes the remaining constraint $G_{12}(\overline{X})$ mentioned in Chapter IV as well as an additional constraint.

In the "matching" problem, the selected propeller, as defined by $\overline{X3}$, must satisfy two conditions. First, it must develop, as a minimum, the effective horsepower (P_E) as imposed by the design specification. Citing the formulation previously derived in Chapter VII, this condition can be stated as:

$$P_E \leq (P_E)_{dev} \tag{9.3}$$

The constraint $G_{12}(\overline{X3})$ follows accordingly as:

$$G_{12}(\overline{X3}) = 1 - \frac{(P_E)_{dev}}{P_E} \leq 0 \tag{9.4}$$

For the second condition, the selected propeller can only absorb, as a maximum, the delivered power (P_D) as

specified by the designer. The formulation is the same as that in Chapter VIII except that the inequality signs are reversed. The condition is stated as:

$$(P_D)_{absorb} \leq P_D \tag{9.5}$$

In defining a constraint $G_{13}(\overline{X3})$, another location, say location 24, in the GLOBCM block (see Table (III)) would be assigned. But, considering the fact that constraint $G_9(\overline{X})$ will not be used because the propeller diameter (D) is specified, there is no reason why $G_9(\overline{X3})$ cannot be redefined, for this Design Case only, as:

$$G_9(\overline{X3}) = \frac{(P_D)_{absorb}}{P_D} - 1 \leq 0 \tag{9.6}$$

Further simplification of equation (9.6) gives:

$$G_9(\overline{X3}) = \frac{Q_P}{Q_S} - 1 \leq 0 \tag{9.7}$$

In reality, the constraints just defined should be equality constraints. The word "match" does infer equality in some sense. However, as previously stated in Chapter II, the version of COPES/CONMIN used in this study does not directly handle equality constraints. But, since CONMIN attempts to minimize constraints in the optimization search, it will be assumed that a "match" can be achieved.

With the design vector $\overline{X3}$ and the constraints $G_{12}(\overline{X3})$ and $G_9(\overline{X3})$ defined, the propeller selection problem represented by Design Case No. 3 can now be stated under one equation as:

$$\text{Minimize:} \quad F(\overline{X3}) = OBJ_3$$

$$\text{Subject to:} \quad G_j(\overline{X3}) \leq 0 \qquad j = 1,\ldots,12 \tag{9.8}$$

$$X3_i^{lower} \leq X_i \leq X3_i^{upper} \qquad i = 1,\ldots,3$$

C. PREVIOUS SOLUTIONS

The propeller selection problem considered by Vassilopoulos [Ref. 18] actually represents a propeller "design" problem using the "power" approach. The example problem which he elected to solve is taken from that posed by the International Towing Tank Conference (ITTC) Propeller Committee. This problem is concerned with the determination of propeller thrust (T), diameter (D) and speed of advance (V_A) (or ship speed (V)) for a single-screw cargo ship where:

1) power available to the propeller (i.e., P_D) is 30,000 (hp)

2) $Z = 6$

3) $N = 105$--110 (rpm)

4) $D_{lim} = 23$ (ft)

5) $h_{c\ell} = 19$ (ft)

The variation of ship speed (V) and of hull effective power (P_E), thrust deduction factor (td) and the wake fraction (wt) is also given [Ref. 18: p. 20].

The results from Vassilopoulos' propeller design exercise produced a propeller that is "matched" at the following values:

1) $P_E = 21292.6$ (hp)
2) $V = 24.24$ (knots)
3) $Q_S = 1500606.75$ (ft-lbf)
4) $N_P = 105$ (rpm)
5) $P_D = 30000.0$ (hp)

His propeller "design" was based upon the following specified parameters:

1) Temp = 59 (°F)
2) $\rho = 1.9905$ (lbf-sec^2/ft^4)
3) $p_{watvap} = .247$ (psia)
4) wt = .22
5) td = .1725
6) noscrw = 1
7) $h_{c\ell} = 19.0$ (ft)
8) Z = 6
9) promat = 5 (stainless teel, see Table (II))
10) D = 22.0 (ft)
11) $N_P = 105$ (rpm)
12) $P_D = 30000.0$ (hp)

Using an optimization scheme incorporated in his MVAPDP computer program, Vassilopoulos maximized the open water efficiency (η_o) and designed a propeller with the following characteristics:

1) J = .852
2) $K_T = .242$

3) $K_Q = .0478$

4) $\eta_o = .691$

5) $A_E/A_O = .767$

6) bldwt = 7617.2 (lbf)

By utilizing both the lifting line and lifting surface methods in his design procedure, Vassilopoulos' MVAPDP program evolved a "constant stress" propeller blade. Consequently, the values for (t*/c) and P/D varied non-linearly along the propeller radius (R). According to Vassilopoulos, this resulted in a minimum weight propeller. The values for P/D and (t*/c) are listed in Tables (8) and (10) of his paper. From these values, $(t^*/c)_{.75R}$ is approximately .040.

While the propeller represented by Vassilopoulos' design is different, in many aspects (rake, skew, blade section aerfoil shape, etc.), from the Wageningen B-Screw Series propeller, it does represent a minimum weight propeller that has been "matched" to specific design values. Appropriate results are summarized in Table (VI).

D. SOLUTIONS BY COPES/CONMIN

The propeller selection problem, as stated by equation (9.8), is now solved by COPES/CONMIN. One solution variation is considered. The following parameters are used:

1) Temp = 59 (°F)

2) $\rho = 1.9905$ (lbf-sec^2/ft^4)

3) $\nu = 1.2817 \times 10^{-5}$ (ft^2/sec)

4) $p_{watvap} = .247$ (psia)

5) p_{atm} = 14.7 (psia)

6) wt = .22

7) η_R = 1.025

8) noscrw = 1

9) $h_{c\ell}$ = 19.0 (ft)

10) Z = 6

11) promat = 5 (stainless steel, see Table (II))

12) D = 22.0 (ft)

Two problems are examined. Problem 1 specifies the following additional parameters:

1) td = .1725

2) P_E = 21292.6 (hp)

3) V = 24.24 (knots)

4) Q_S = 1500606.75 (ft-lbf)

5) N_P = 105 (rpm)

Problem 2 specifies the same parameters as:

1) td = .171

2) P_E = 17630.0 (hp)

3) V = 23.0 (knots)

4) Q_S = 1500606.75 (ft-lbf)

5) N_P = 105 (rpm)

All of the above are initialized in the input section (ICALC = 1) of similar versions of SUBROUTINE ANALIZ. Therefore, only one version is included in Appendix I.

The constraints for $G_9(\overline{X3})$ and $G_{12}(\overline{X3})$ are evaluated by SUBROUTINE BLPOW3 which appears in the execution section of

SUBROUTINE ANALIZ. Also, note that SUBROUTINE DICNUA has been deleted from the execution section, while SUBROUTINE WGTCAL has been added.

1. Programming Details

All twelve constraints are evaluated (NCON = 12). The upper ($X3_i^{upper}$) and lower ($X3_i^{lower}$) limits on the design variables P/D, A_E/A_O and $(t^*/c)_{.75R}$ are set to be:

$$.4 \leq P/D \leq 1.4$$

$$.4 \leq A_E/A_O \leq 1.1$$

$$.003 \leq (t^*/c)_{.75R} \leq .50$$

These upper and lower limits are specified in the COPES control card deck on card image F under respective fields VUB and VLB. The initial value for each design variable ($X3_i$) is also assigned on card image F under the field labeled X. The list of card images in Appendix J lists all of the COPES control cards used for both problems. These cards also specify the locations of the design variables in the common block GLOBCM (see Table (III)) as well as the locations of the constraints and their boundaries. Further details on the COPES control card requirements and the format of each card are contained in Reference [7].

2. Results

The outputs from the optimization/analysis, performed by COPES/CONMIN, are listed in Appendix K. Results of both problems are tabulated in Table (VI).

E. DISCUSSION

Table (VI) presents the results of problems 1 and 2 along with relevant information from Vassilopoulos' "design". Problem 1 attempted to "match" a Wageningen propeller at the design point found by Vassilopoulos. The first COPES/CONMIN printout in Appendix K indicates that the "match" was achieved at P_E equal to 21.168.1 (hp) and P_D equal to 28,150.0 (hp) (or, Q_S = 1500607 (ft-lbf) and N_P = 105 (rpm)). These values are judged to be close enough to the "Given" values in Table (VI).

It is apparent that the Wageningen propeller does not require all of the 30,000 (hp) of delivered horsepower. The propeller characteristics (i.e., J, K_T, K_Q and η_o) for problem 1 compare very well to Vassilopoulos' values. The expanded area ratios (A_E/A_O) are, also, very similar. Of course, the obvious difference is the blade weight (bldwt). The Wageningen propeller blade is over five thousand pounds heavier. Does this make sense for a minimum blade weight?

The answer is yes.

All one has to do is consider the values of (t*/c) for problem 1 and Vassilopoulos' design. Vassilopoulos' "constant stress" blade was designed to "absorb" stress up to the allowable design limit of 5,400 (psi) (for stainless steel) <u>all along</u> the entire propeller radius (R). Table (12) in Reference [18] gives further details. The Wageningen propeller blade, however, represents an "older" type of blade which was designed with a <u>linear</u> blade section maximum thickness (t*)

distribution. Consequently, it was "overdesigned" for strength beyond the 3/10--4/10 radius (i.e., .3R--.4R) and contains excess material. A heavier blade, therefore, results. Note, also, that the optimizer did not drive the value of $(t^*/c)_{.75R}$ to the minimum acceptable value, $(t^*/c)_{.75R\,min}$.

The results of problem 2 show the effect on blade weight (bldwt) for a Wageningen propeller when the hull's powering requirements (i.e., P_E at V) have been reduced. The weight reduction of 2000 pounds is significant. The complete results are listed in the second COPES/CONMIN printout in Appendix K.

TABLE VI

Design Case No. 3--Results

GROUP	ITEM	VASSILOPOULOS	PROBLEM 1	PROBLEM 2
Given	P_E	21292.6	21292.6	17630.0
	V	24.24	24.24	23.0
	Q_S	1500607	1500607	1500607
	N_P	105	105	105
Design Variable Specified	D	22.0	22.0	22.0
Design Variables	P/D	*	1.1813	1.0906
	A_E/A_O	.767	.7944	.7742
	$(t^*/c)_{.75R}$	.040	.0794	.0681
Minimize	bldwt	—	12842.6	10464.7
Maximize	η_o	.691	—	—
Restrictions	D_{lim}	—	—	—
	$A_E/A_{O\,min}$	—	.8515	.7722
	$(t^*/c)_{.75Rmin}$	—	.0691	.0681
Other	J	.852	.8290	.7866
	K_T	.242	.2349	.2063
	K_Q	.0478	.0448	.0372
	η_o	—	.6915	.6950
	bldwt	7617.2	—	—

*P/D varies with R

X. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The general purpose non-linear optimizer/synthesizer COPES/CONMIN has been successfully applied to three typical preliminary ship design propeller selection problems in which the Wageningen B-Screw Series is used. The formulation and programming of each required analysis code (i.e., SUBROUTINE ANALIZ) have been made as general as possible to allow the designer a broad variety of solution options for solving propeller selection problems which can be classified under any of the three Design Cases that were considered. The analysis codes have been "modularized" to the extent that methodical series data from other propeller series, which are available in the polynomial expression format of the B-Screw Series, can be easily adapted for powering analysis utilizing design optimization methods.

Further flexibility in the solution to the propeller selection problem has been achieved by using COPES/CONMIN as the optimizer/synthesizer. The designer has now been afforded the additional capability of specifying the design variables, the objective functions and the constraints of his choice. By solving propeller selection problems in the way presented in this thesis, repetitive problem formulation and coding have been eliminated.

There are other advantages to solving propeller selection problems specifically with COPES/CONMIN which have not been

directly addressed in this study. As stated in Chapter II, COPES/CONMIN is capable of performing optimization analyses, sensitivity studies, optimum sensitivity studies and optimization using approximation techniques. The designer, therefore, can select and perform any of these options, using the same analysis codes which have been presented in this thesis.

While the utilization of a general purpose non-linear optimizer in solving propeller selection problems allows the designer greater flexibility in the selection procedure, there is one important limitation that should be stressed at this point. This concerns the question whether or not the solution vector, determined by the optimizer, is a "global" optimum. As stated in Chapter II, COPES/CONMIN assures that, if a feasible solution vector is found, it is, at least, a "local" minimum (or maximum). This implies that, for two different initial design vectors which are specified in the COPES Control Card deck on card image F, the same optimum solution may not be determined by the optimizer. Both solutions would correspond to minimums (or maximums) of the objective function and are, therefore, correct. But, does one or the other correspond to the minimum (or maximum) of the entire vector design space, i.e., the "global" optimum? For the moment, at least, there is no definitive answer to the question.

Despite this uncertainty, progress in the field of design optimization continues to be made. Current developments [Ref. 47] will soon allow the designer to have a choice in

selecting a specific optimization algorithm from a "library" of proven optimization programs which employ the latest state-of-theart numerical techniques. Again, using one analysis code, the designer will be able to generate any number of optimized solutions for the problem under study.

B. RECOMMENDATIONS

For future consideration, it is recommended that the automated design and trade-off capability, provided by a general purpose non-linear optimizer/synthesizer such as COPES/CONMIN, be applied to the more difficult problem of propeller design.

As pointed out in Chapter I, the use of the Wageningen B-Screw Series represents a "selection" procedure rather than a "design" process. Today, analytical propeller design procedures, utilizing lifting line and lifting surface theory, are becoming increasingly popular among propeller designers. The propeller design, which results from the utilization of these analytical methods, is, unquestionably, more efficient than the standard series propeller. However, these methods require consideration of many more design variables in the design process. This appears to be a natural application for the use of a general purpose non-linear optimizer/synthesizer.

Here, an analysis code, much larger than those which have been presented in this study, could be developed which would incorporate the lifting line/lifting surface theory

for the determination of the propeller performance characteristics, the local cavitation numbers and also the calculation of the pressure distributions over the blade. These pressure distributions would be utilized in the strength analysis of the blade. This analysis would utilize the finite element technique on an appropriately generated mesh model of the blade. Having defined the steps for this design procedure in the analysis code, the propeller designer now "couples" his analysis to the optimizer/synthesizer for determination of the optimum design. A massive amount of computer storage would certainly be required, but this concept is feasible and, in the author's view, is worthy of future consideration.

C. A FINAL NOTE

In conclusion, this thesis has demonstrated, in effect, another interesting application of the method of design optimization. The author, in no way, wishes to leave the reader with the impression that the techniques of design optimization are the "be all--end all" for engineering analysis. Design optimization techniques are useful and powerful tools that stand to relieve the engineer of the mundane tasks of numerical calculations and subsequent graphic plotting. But, they are just tools. In the final "analysis", good engineering judgment is paramount in their application and use.

APPENDIX A

FORTRAN VARIABLE CROSS REFERENCE LIST

Symbol	Fortran Variable
A_E/A_O	AEDVAO
$(A_E/A_O)_{min}$	AEAOMN
bldwt	WEIGHT
$c_{.75R}$	C75R
D	DIA
D_{lim}	DIALIM
$h_{c\ell}$	HCL
J	RJ
K_Q	KQ
K_T	KT
noscrw	NOSCRW
N_P	N
P_E	PE
P_D	PD
P/D	PDIVD
p_{watvap}	PWATVA
p_{atm}	PATM
promat	PROMAT
Q_S	QS
$Rn^*_{.75R}$	R75R
S_c	SC
td	TD

Symbol	Fortran Variable
Temp	TEMP
$(t^*/c)_{.75R}$	TC75R
V (ft/sec)	V
V (knots)	VK
wt	WT
Z	Z
η_o	ETAO
η_R	ETARR
ν	WATNU
ρ	WATRO

APPENDIX B

SUBROUTINE LISTINGS

```
      SUBROUTINE ELDPRP
C
C
C     SUBROUTINE:  BLCPRP                          DATE OF LAST REVISION: APR 83
C
C     INPUT             OUTPUT                     DEFINITION
C
C     AEDVAO                                       EXPANDED AREA RATIO
C     DIA                                          PROPELLER DIAMETER (FEET)
C     Z                                            NO. OF PROPELLER BLADES
C     COMMON /THICD/                               BLADE SECTION MAXIMUM
C                                                  THICKNESSESS ALONG PROPELLER
C                                                  RADIUS (FEET)
C                       COMMON/AREBLD/             BLADE SECTION AREAS (FEET**2)
C                       COMMON/CGX/                LOCATION OF BLADE CROSS-SEC-
C                                                  TIONAL AREA CENTROID WITH
C                                                  RESPECT TO GENERATOR LINE
C                                                  (FEET)
C                       COMMON/CGY/                LOCATION OF BLADE CROSS-SEC-
C                                                  TICNAL AREA CENTROID WITH
C                                                  RESPECT TO PITCH-REFERENCE
C                                                  LINE (FEET)
C                       COMMON/CRDLNT/             BLADE SECTION CHORD LENGTHS
C                                                  (FEET)
C                       COMMON/VALU1/              ORDINATE OF CRITICAL POINT NO.
C                                                  1 ON BLADE SECTION PERIPHERY
C                                                  WITH RESPECT TO A SYSTEM OF
C                                                  AXES PARALLEL AND NORMAL TO
C                                                  PITCH-REFERENCE LINE WITH ORI-
C                                                  GIN AT THE CENTROID OF THE
C                                                  SECTION (FEET)
C                       COMMON/VALW1/              ABCISSA OF CRITICAL POINT NO.
C                                                  1 ON BLADE SECTION PERIPHERY
C                                                  WITH RESPECT TO A SYSTEM OF
C                                                  AXES PARALLEL AND NORMAL TO
C                                                  PITCH-REFERENCE LINE WITH ORI-
C                                                  GIN AT THE CENTROID OF THE
C                                                  SECTION (FEET)
C                       COMMON/VALU2/              ORDINATE OF CRITICAL POINT NO.
C                                                  2 ON BLADE SECTION PERIPHERY
C                                                  WITH RESPECT TO A SYSTEM OF
C                                                  AXES PARALLEL AND NORMAL TO
C                                                  PITCH-REFERENCE LINE WITH ORI-
C                                                  GIN AT THE CENTROID OF THE
C                                                  SECTION (FEET)
C                       COMMON/VALW2/              ABCISSA OF CRITICAL POINT NO.
C                                                  2 ON BLADE SECTION PERIPHERY
C                                                  WITH RESPECT TO A SYSTEM OF
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C                                     AXES PARALLEL AND NORMAL TO    APP00490
C                                     PITCH-REFERENCE LINE WITH ORI-APP00500
C                                     GIN AT THE CENTROID OF THE     APP00510
C                                     SECTION (FEET)                 APP00520
C               COMMON/VALU3/         ORDINATE OF CRITICAL POINT NO.APP00530
C                                     3 ON BLADE SECTION PERIPHERY   APP00540
C                                     WITH RESPECT TO A SYSTEM OF    APP00550
C                                     AXES PARALLEL AND NORMAL TO    APP00560
C                                     PITCH-REFERENCE LINE WITH ORI-APP00570
C                                     GIN AT THE CENTROID OF THE     APP00580
C                                     SECTION (FEET)                 APP00590
C               COMMON/VALW3/         ABCISSA OF CRITICAL POINT NO.  APP00600
C                                     3 ON BLADE SECTION PERIPHERY   APP00610
C                                     WITH RESPECT TO A SYSTEM OF    APP00620
C                                     AXES PARALLEL AND NORMAL TO    APP00630
C                                     PITCH-REFERENCE LINE WITH ORI-APP00640
C                                     GIN AT THE CENTROID OF THE     APP00650
C                                     SECTION (FEET)                 APP00660
C               COMMON/VALU4/         ORDINATE OF CRITICAL POINT NO.APP00670
C                                     4 ON BLADE SECTION PERIPHERY   APP00680
C                                     WITH RESPECT TO A SYSTEM OF    APP00690
C                                     AXES PARALLEL AND NORMAL TO    APP00700
C                                     PITCH-REFERENCE LINE WITH ORI-APP00710
C                                     GIN AT THE CENTROID OF THE     APP00720
C                                     SECTION (FEET)                 APP00730
C               COMMON/VALW4/         ABCISSA OF CRITICAL POINT NO.  APP00740
C                                     4 ON BLADE SECTION PERIPHERY   APP00750
C                                     WITH RESPECT TO A SYSTEM OF    APP00760
C                                     AXES PARALLEL AND NORMAL TO    APP00770
C                                     PITCH-REFERENCE LINE WITH ORI-APP00780
C                                     GIN AT THE CENTROID OF THE     APP00790
C                                     SECTION (FEET)                 APP00800
C               COMMON/A2MOMX/        MOMENT OF INERTIA ABOUT NEU-   APP00810
C                                     TRAL AXIS PARALLEL TO GENERA-  APP00820
C                                     TOR LINE, PASSING THROUGH      APP00830
C                                     BLADE CROSS SECTION CENTROID   APP00840
C                                     (FEET**4)                      APP00850
C               COMMON/A2MOMY/        MOMENT OF INERTIA ABOUT NEU-   APP00860
C                                     TRAL AXIS PARALLEL TO PITCH    APP00870
C                                     REFERENCE LINE,PASSING THROUGHAPP00880
C                                     BLADE CROSS SECTION CENTROID   APP00890
C                                     (FEET**4)                      APP00900
C                                                                    APP00910
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,           APP00920
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,  APP00930
     2       FCWBAL,DIACNU,AEAOCV,TCSTRS,                            APP00940
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,            APP00950
     4       PWATVA,PROMAT,DIALIM,ETARR,                             APP00960
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     5         RJ,C75R,R75R,KT,KQ                                             APP00970
      REAL*4   T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,T90R,         APP00980
     1         T100R,RAT                                                       APP00990
      REAL*4   CR(10),AR(10),BR(10),PLF(10),PLA(10),TR(10),V1F(10,11),         APP01000
     1         V2F(10,11),V1A(10,10),V2A(10,10),YFACE(11),YBACK(11),           APP01010
     2         FA(10),Y(11),DELPA(10),AA(10),DLPASM,XA(10),YA(10),SUMAA,       APP01020
     3         SUMAXA,SUMAYA,SMAX2A,SMAY2A,FF(11),DELPF(11),AF(11),DLPFSM,APP01030
     4         XF(11),YF(11),SUMAF,SUMAXF,SUMAYF,SMAX2F,SMAY2F,AREA(10),       APP01040
     5         XMT(10),YPRL(10),RIXXNA(10),RIYYNA(10),XCG(10),YCG(10)          APP01050
      REAL*4   U1(10),U2(10),U3(10),U4(10),W1(10),W2(10),W3(10),W4(10),         APP01060
     1         YBK,YFC,DN                                                      APP01070
      INTEGER*4 I,IR,IP1                                                       APP01080
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNL,APP01090
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,           APP01100
     2AEACCV,TCSTRS,RJ                                                          APP01110
      COMMON /PARAM/ VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,     APP01120
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                                     APP01130
      COMMON /THICD/TCOR,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,       APP01140
     1T90R,T1CCR,RAT                                                           APP01150
      COMMON /AREELD/AREA                                                      APP01160
      COMMON /CGX/XCG                                                          APP01170
      COMMON /CGY/YCG                                                          APP01180
      COMMON /CRDLNT/CR                                                        APP01190
      COMMON /VALU1/U1                                                         APP01200
      COMMON /VALU2/U2                                                         APP01210
      COMMON /VALU3/U3                                                         APP01220
      COMMON /VALU4/U4                                                         APP01230
      COMMON /VALW1/W1                                                         APP01240
      COMMON /VALW2/W2                                                         APP01250
      COMMON /VALW3/W3                                                         APP01260
      COMMON /VALW4/W4                                                         APP01270
      COMMON /A2MCMX/RIYYNA                                                    APP01280
      COMMON /A2MCMY/RIXXNA                                                    APP01290
C                                                                              APP01300
C     DETERMINE CHORD LENGTHS ALONG BLADE RADIUS USING TABLE (1), REF 2 APP01310
C                                                                              APP01320
      IF(.NOT.(Z.EQ.3.0))GO TO 1                                               APP01330
         CR(1)=(1.5932*AEDVAO*DIA)/Z                                           APP01340
      GO TO 5                                                                  APP01350
    1 CONTINUE                                                                 APP01360
      IF(.NOT.(Z.EQ.4.0))GO TO 2                                               APP01370
         CR(1)=(1.5894*AEDVAO*DIA)/Z                                           APP01380
      GO TO 5                                                                  APP01390
    2 CONTINUE                                                                 APP01400
      IF(.NOT.(Z.EQ.5.0))GO TO 3                                               APP01410
         CR(1)=(1.5894*AEDVAO*DIA)/Z                                           APP01420
      GO TO 5                                                                  APP01430
    3 CONTINUE                                                                 APP01440
```

```
      IF(.NOT.(Z.EQ.6.0))GO TO 4
            CR(1)=(1.5894*AEDVAO*DIA)/Z
      GO TO 5
    4 CONTINUE
            CR(1)=(1.6180*AEDVAO*DIA)/Z
    5 CONTINUE
      IF(.NOT.(Z.EQ.3.0))GO TO 6
            CR(2)=(1.6330*AEDVAO*DIA)/Z
            CR(3)=(1.8320*AEDVAO*DIA)/Z
            CR(4)=(2.0000*AEDVAO*DIA)/Z
            CR(5)=(2.1200*AEDVAO*DIA)/Z
            CR(6)=(2.1860*AEDVAO*DIA)/Z
            CR(7)=(2.1680*AEDVAO*DIA)/Z
            CR(8)=(2.1270*AEDVAO*DIA)/Z
            CR(9)=(1.6570*AEDVAO*DIA)/Z
            CR(10)=(0.000*AEDVAO*DIA)/Z
      GO TO 7
    6 CONTINUE
            CR(2)=(1.6620*AEDVAO*DIA)/Z
            CR(3)=(1.8820*AEDVAO*DIA)/Z
            CR(4)=(2.0500*AEDVAO*DIA)/Z
            CR(5)=(2.1520*AEDVAO*DIA)/Z
            CR(6)=(2.1870*AEDVAO*DIA)/Z
            CR(7)=(2.1440*AEDVAO*DIA)/Z
            CR(8)=(1.9700*AEDVAO*DIA)/Z
            CR(9)=(1.5820*AEDVAO*DIA)/Z
            CR(10)=(0.000*AEDVAO*DIA)/Z
    7 CONTINUE
C
C     CALCULATE POSITION OF GENERATOR LINE (I.E., AR(I)) AND POSITION OF
C     MAXIMUM BLADE SECTION THICKNESS (I.E., BR(I)) USING FIGURE (1) AND
C     TABLE (1), REF 2
C
      IF(.NOT.(Z.EQ.3.0))GO TO 8
            AR(1)=0.617*CR(1)
            BR(1)=0.350*CR(1)
      GO TO 12
    8 CONTINUE
      IF(.NOT.(Z.EQ.4.0))GO TO 9
            AR(1)=0.61832*CR(1)
            BR(1)=0.350*CR(1)
      GO TO 12
    9 CONTINUE
      IF(.NOT.(Z.EQ.5.0))GO TO 10
            AR(1)=0.61832*CR(1)
            BR(1)=0.350*CR(1)
      GO TO 12
   10 CONTINUE
```

```
      IF(.NOT.(Z.EQ.6.0))GO TO 11
            AR(1)=0.61832*CR(1)
            BR(1)=0.350*CR(1)
      GO TO 12
   11 CONTINUE
            AR(1)=0.6178*CR(1)
            BR(1)=0.350*CR(1)
   12 CONTINUE
      IF(.NOT.(Z.EQ.3.0))GO TO 13
            AR(2)=0.616*CR(2)
            AR(3)=0.611*CR(3)
            AR(4)=0.599*CR(4)
            AR(5)=0.583*CR(5)
            AR(6)=0.558*CR(6)
            AR(7)=0.526*CR(7)
            AR(8)=0.481*CR(8)
            AR(9)=0.400*CR(9)
            AR(10)=0.0
            BR(2)=0.350*CR(2)
            BR(3)=0.350*CR(3)
            BR(4)=0.350*CR(4)
            BR(5)=0.355*CR(5)
            BR(6)=0.389*CR(6)
            BR(7)=0.442*CR(7)
            BR(8)=0.478*CR(8)
            BR(9)=0.500*CR(9)
            BR(10)=0.0
      GO TO 14
   13 CONTINUE
            AR(2)=0.617*CR(2)
            AR(3)=0.613*CR(3)
            AR(4)=0.601*CR(4)
            AR(5)=0.586*CR(5)
            AR(6)=0.561*CR(6)
            AR(7)=0.524*CR(7)
            AR(8)=0.463*CR(8)
            AR(9)=0.351*CR(9)
            AR(10)=0.0
            BR(2)=0.350*CR(2)
            BR(3)=0.350*CR(3)
            BR(4)=0.351*CR(4)
            BR(5)=0.355*CR(5)
            BR(6)=0.389*CR(6)
            BR(7)=0.443*CR(7)
            BR(8)=0.479*CR(8)
            BR(9)=0.500*CR(9)
            BR(10)=0.0
   14 CONTINUE
```

```
C                                                                       APP02410
C     DETERMINE "FORWARD" (P=0 TO P=+1) AND "AFT" (P=0 TO P=-1)         APP02420
C     INTEGRATION INTERVALS WITH RESPECT TO PITCH-REFERENCE LINE FOR    APP02430
C     EACH BLADE SECTION ALONG PROPELLER BLADE RADIUS USING FIGURE (1)  APP02440
C     AND TABLE (1), REF 2                                              APP02450
C                                                                       APP02460
      DO 15 I=1,10                                                      APP02470
            PLF(I)=BR(I)                                                APP02480
            PLA(I)=CR(I)-PLF(I)                                         APP02490
   15 CONTINUE                                                          APP02500
C                                                                       APP02510
C     INITIALIZE MAXIMUM BLADE SECTION THICKNESS ALONG PROPELLER BLADE  APP02520
C     RADIUS                                                            APP02530
C                                                                       APP02540
      TR(1)=T1XR                                                        APP02550
      TR(2)=T2CR                                                        APP02560
      TR(3)=T3CR                                                        APP02570
      TR(4)=T4CR                                                        APP02580
      TR(5)=T5CR                                                        APP02590
      TR(6)=T6CR                                                        APP02600
      TR(7)=T7CR                                                        APP02610
      TR(8)=T8CR                                                        APP02620
      TR(9)=T9CR                                                        APP02630
      TR(10)=T10OR                                                      APP02640
C                                                                       APP02650
C     INITIALIZE VALUES FOR "V1" & "V2" (P=0 TO P=+1) AND "V1" & "V2"   APP02660
C     (P=0 TO P=-1) IN RELATIONS (2) AND (3), REF 2, USING VALUES FROM  APP02670
C     TABLE (2), REF 2                                                  APP02680
C                                                                       APP02690
C     ... BEGIN AT R=.18R FOR PROPELLERS WITH 3 OR 7 BLADES             APP02700
C                                                                       APP02710
      IF(.NOT.((Z.EQ.3.0).OR.(Z.EQ.7.0)))GO TO 16                       APP02720
            V1F(1,1)=0.0000                                             APP02730
            V1F(1,2)=0.0063                                             APP02740
            V1F(1,3)=0.0336                                             APP02750
            V1F(1,4)=0.0558                                             APP02760
            V1F(1,5)=0.0851                                             APP02770
            V1F(1,6)=0.1238                                             APP02780
            V1F(1,7)=0.1761                                             APP02790
            V1F(1,8)=0.2092                                             APP02800
            V1F(1,9)=0.2466                                             APP02810
            V1F(1,10)=0.2947                                            APP02820
            V1F(1,11)=0.3678                                            APP02830
            V1A(1,1)=0.0000                                             APP02840
            V1A(1,2)=0.0232                                             APP02850
            V1A(1,3)=0.0722                                             APP02860
            V1A(1,4)=0.1028                                             APP02870
            V1A(1,5)=0.1352                                             APP02880
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      V1A(1,6)=0.1713                                                 APP02890
      V1A(1,7)=0.2098                                                 APP02900
      V1A(1,8)=0.2505                                                 APP02910
      V1A(1,9)=0.2715                                                 APP02920
      V1A(1,10)=0.2905                                                APP02930
      V2F(1,1)=1.0000                                                 APP02940
      V2F(1,2)=0.9752                                                 APP02950
      V2F(1,3)=0.8860                                                 APP02960
      V2F(1,4)=0.8126                                                 APP02970
      V2F(1,5)=0.7213                                                 APP02980
      V2F(1,6)=0.6116                                                 APP02990
      V2F(1,7)=0.4680                                                 APP03000
      V2F(1,8)=0.3813                                                 APP03010
      V2F(1,9)=0.2749                                                 APP03020
      V2F(1,10)=0.1463                                                APP03030
      V2F(1,11)=0.0000                                                APP03040
      V2A(1,1)=1.0000                                                 APP03050
      V2A(1,2)=0.9414                                                 APP03060
      V2A(1,3)=0.7915                                                 APP03070
      V2A(1,4)=0.6909                                                 APP03080
      V2A(1,5)=0.5744                                                 APP03090
      V2A(1,6)=0.4438                                                 APP03100
      V2A(1,7)=0.2986                                                 APP03110
      V2A(1,8)=0.1406                                                 APP03120
      V2A(1,9)=0.0602                                                 APP03130
      V2A(1,10)=0.0000                                                APP03140
   GO TO 17                                                           APP03150
C                                                                     APP03160
C  ... OR BEGIN AT R=.167R FOR PROPELLERS WITH 4,5,OR 6 BLADES        APP03170
C                                                                     APP03180
16 CONTINUE                                                           APP03190
      V1F(1,1)=0.0000                                                 APP03200
      V1F(1,2)=0.0076                                                 APP03210
      V1F(1,3)=0.0357                                                 APP03220
      V1F(1,4)=0.0529                                                 APP03230
      V1F(1,5)=0.0881                                                 APP03240
      V1F(1,6)=0.1274                                                 APP03250
      V1F(1,7)=0.1808                                                 APP03260
      V1F(1,8)=0.2152                                                 APP03270
      V1F(1,9)=0.2541                                                 APP03280
      V1F(1,10)=0.3033                                                APP03290
      V1F(1,11)=0.3756                                                APP03300
      V1A(1,1)=0.0000                                                 APP03310
      V1A(1,2)=0.0282                                                 APP03320
      V1A(1,3)=0.0817                                                 APP03330
      V1A(1,4)=0.1134                                                 APP03340
      V1A(1,5)=0.1457                                                 APP03350
      V1A(1,6)=0.1812                                                 APP03360
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      V1A(1,7)=0.2184
      V1A(1,8)=0.2569
      V1A(1,9)=0.2764
      V1A(1,10)=0.2946
      V2F(1,1)=1.0000
      V2F(1,2)=0.9754
      V2F(1,3)=0.8847
      V2F(1,4)=0.8096
      V2F(1,5)=0.7167
      V2F(1,6)=0.6065
      V2F(1,7)=0.4613
      V2F(1,8)=0.3751
      V2F(1,9)=0.2686
      V2F(1,10)=0.1395
      V2F(1,11)=0.0000
      V2A(1,1)=1.0000
      V2A(1,2)=0.9391
      V2A(1,3)=0.7868
      V2A(1,4)=0.6850
      V2A(1,5)=0.5676
      V2A(1,6)=0.4372
      V2A(1,7)=0.2936
      V2A(1,8)=0.1372
      V2A(1,9)=0.0576
      V2A(1,10)=0.0000
   17 CONTINUE
C
C     ... CONTINUE FOR R=.2R
C
      V1F(2,1)=0.0000
      V1F(2,2)=0.0049
      V1F(2,3)=0.0304
      V1F(2,4)=0.0502
      V1F(2,5)=0.0804
      V1F(2,6)=0.1180
      V1F(2,7)=0.1685
      V1F(2,8)=0.2000
      V1F(2,9)=0.2353
      V1F(2,10)=0.2821
      V1F(2,11)=0.3560
      V1A(2,1)=0.0000
      V1A(2,2)=0.0172
      V1A(2,3)=0.0592
      V1A(2,4)=0.0880
      V1A(2,5)=0.1207
      V1A(2,6)=0.1570
      V1A(2,7)=0.1967
      V1A(2,8)=0.2400
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      V1A(2,9)=0.2630                                                   APP03850
      V1A(2,10)=0.2826                                                  APP03860
      V2F(2,1)=1.0000                                                   APP03870
      V2F(2,2)=0.9750                                                   APP03880
      V2F(2,3)=0.8875                                                   APP03890
      V2F(2,4)=0.8170                                                   APP03900
      V2F(2,5)=0.7277                                                   APP03910
      V2F(2,6)=0.6190                                                   APP03920
      V2F(2,7)=0.4777                                                   APP03930
      V2F(2,8)=0.3905                                                   APP03940
      V2F(2,9)=0.2840                                                   APP03950
      V2F(2,10)=0.1560                                                  APP03960
      V2F(2,11)=0.0000                                                  APP03970
      V2A(2,1)=1.0000                                                   APP03980
      V2A(2,2)=0.9446                                                   APP03990
      V2A(2,3)=0.7984                                                   APP04000
      V2A(2,4)=0.6995                                                   APP04010
      V2A(2,5)=0.5842                                                   APP04020
      V2A(2,6)=0.4535                                                   APP04030
      V2A(2,7)=0.3060                                                   APP04040
      V2A(2,8)=0.1455                                                   APP04050
      V2A(2,9)=0.0640                                                   APP04060
      V2A(2,10)=0.0000                                                  APP04070
C                                                                       APP04080
C     ... CONTINUE FOR R=.3R                                            APP04090
C                                                                       APP04100
      V1F(3,1)=0.0000                                                   APP04110
      V1F(3,2)=0.0027                                                   APP04120
      V1F(3,3)=0.0148                                                   APP04130
      V1F(3,4)=0.0300                                                   APP04140
      V1F(3,5)=0.0503                                                   APP04150
      V1F(3,6)=0.0709                                                   APP04160
      V1F(3,7)=0.1191                                                   APP04170
      V1F(3,8)=0.1445                                                   APP04180
      V1F(3,9)=0.1760                                                   APP04190
      V1F(3,10)=0.2186                                                  APP04200
      V1F(3,11)=0.2923                                                  APP04210
      V1A(3,1)=0.0000                                                   APP04220
      V1A(3,2)=0.0033                                                   APP04230
      V1A(3,3)=0.0202                                                   APP04240
      V1A(3,4)=0.0376                                                   APP04250
      V1A(3,5)=0.0623                                                   APP04260
      V1A(3,6)=0.0943                                                   APP04270
      V1A(3,7)=0.1333                                                   APP04280
      V1A(3,8)=0.1790                                                   APP04290
      V1A(3,9)=0.2040                                                   APP04300
      V1A(3,10)=0.2306                                                  APP04310
      V2F(3,1)=1.0000                                                   APP04320
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      V2F(3,2)=0.9750                                                   APP04330
      V2F(3,3)=0.8920                                                   APP04340
      V2F(3,4)=0.8315                                                   APP04350
      V2F(3,5)=0.7520                                                   APP04360
      V2F(3,6)=0.6505                                                   APP04370
      V2F(3,7)=0.5130                                                   APP04380
      V2F(3,8)=0.4265                                                   APP04390
      V2F(3,9)=0.3197                                                   APP04400
      V2F(3,10)=0.1890                                                  APP04410
      V2F(3,11)=0.0000                                                  APP04420
      V2A(3,1)=1.0000                                                   APP04430
      V2A(3,2)=0.9583                                                   APP04440
      V2A(3,3)=0.8265                                                   APP04450
      V2A(3,4)=0.7335                                                   APP04460
      V2A(3,5)=0.6195                                                   APP04470
      V2A(3,6)=0.4885                                                   APP04480
      V2A(3,7)=0.3360                                                   APP04490
      V2A(3,8)=0.1670                                                   APP04500
      V2A(3,9)=0.0800                                                   APP04510
      V2A(3,10)=0.0000                                                  APP04520
C                                                                       APP04530
C     ... CONTINUE FOR R=.4R                                            APP04540
C                                                                       APP04550
      V1F(4,1)=0.0000                                                   APP04560
      V1F(4,2)=0.0000                                                   APP04570
      V1F(4,3)=0.0033                                                   APP04580
      V1F(4,4)=0.0090                                                   APP04590
      V1F(4,5)=0.0189                                                   APP04600
      V1F(4,6)=0.0357                                                   APP04610
      V1F(4,7)=0.0637                                                   APP04620
      V1F(4,8)=0.0833                                                   APP04630
      V1F(4,9)=0.1088                                                   APP04640
      V1F(4,10)=0.1467                                                  APP04650
      V1F(4,11)=0.2181                                                  APP04660
      V1A(4,1)=0.0000                                                   APP04670
      V1A(4,2)=0.0000                                                   APP04680
      V1A(4,3)=0.0044                                                   APP04690
      V1A(4,4)=0.0116                                                   APP04700
      V1A(4,5)=0.0214                                                   APP04710
      V1A(4,6)=0.0395                                                   APP04720
      V1A(4,7)=0.0630                                                   APP04730
      V1A(4,8)=0.0972                                                   APP04740
      V1A(4,9)=0.1200                                                   APP04750
      V1A(4,10)=0.1467                                                  APP04760
      V2F(4,1)=1.0000                                                   APP04770
      V2F(4,2)=0.9725                                                   APP04780
      V2F(4,3)=0.8933                                                   APP04790
      V2F(4,4)=0.8345                                                   APP04800
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      V2F(4,5)=0.7593                                                   APP04810
      V2F(4,6)=0.6590                                                   APP04820
      V2F(4,7)=0.5220                                                   APP04830
      V2F(4,8)=0.4335                                                   APP04840
      V2F(4,9)=0.3235                                                   APP04850
      V2F(4,10)=0.1935                                                  APP04860
      V2F(4,11)=0.0000                                                  APP04870
      V2A(4,1)=1.0000                                                   APP04880
      V2A(4,2)=0.9645                                                   APP04890
      V2A(4,3)=0.8415                                                   APP04900
      V2A(4,4)=0.7525                                                   APP04910
      V2A(4,5)=0.6353                                                   APP04920
      V2A(4,6)=0.5040                                                   APP04930
      V2A(4,7)=0.3500                                                   APP04940
      V2A(4,8)=0.1810                                                   APP04950
      V2A(4,9)=0.0905                                                   APP04960
      V2A(4,10)=0.0000                                                  APP04970
C                                                                       APP04980
C     ... CONTINUE FOR R=.5R                                            APP04990
C                                                                       APP05000
      V1F(5,1)=0.0000                                                   APP05010
      V1F(5,2)=0.0000                                                   APP05020
      V1F(5,3)=0.0000                                                   APP05030
      V1F(5,4)=0.0008                                                   APP05040
      V1F(5,5)=0.0034                                                   APP05050
      V1F(5,6)=0.0085                                                   APP05060
      V1F(5,7)=0.0211                                                   APP05070
      V1F(5,8)=0.0328                                                   APP05080
      V1F(5,9)=0.0500                                                   APP05090
      V1F(5,10)=0.0778                                                  APP05100
      V1F(5,11)=0.1278                                                  APP05110
      V1A(5,1)=0.0000                                                   APP05120
      V1A(5,2)=0.0000                                                   APP05130
      V1A(5,3)=0.0000                                                   APP05140
      V1A(5,4)=0.0012                                                   APP05150
      V1A(5,5)=0.0040                                                   APP05160
      V1A(5,6)=0.0100                                                   APP05170
      V1A(5,7)=0.0190                                                   APP05180
      V1A(5,8)=0.0330                                                   APP05190
      V1A(5,9)=0.0420                                                   APP05200
      V1A(5,10)=0.0522                                                  APP05210
      V2F(5,1)=1.0000                                                   APP05220
      V2F(5,2)=0.9710                                                   APP05230
      V2F(5,3)=0.8880                                                   APP05240
      V2F(5,4)=0.8275                                                   APP05250
      V2F(5,5)=0.7478                                                   APP05260
      V2F(5,6)=0.6430                                                   APP05270
      V2F(5,7)=0.5039                                                   APP05280
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      V2F(5,8)=0.4135                                                   APP05290
      V2F(5,9)=0.3056                                                   APP05300
      V2F(5,10)=0.1750                                                  APP05310
      V2F(5,11)=0.0000                                                  APP05320
      V2A(5,1)=1.0000                                                   APP05330
      V2A(5,2)=0.9639                                                   APP05340
      V2A(5,3)=0.8456                                                   APP05350
      V2A(5,4)=0.7580                                                   APP05360
      V2A(5,5)=0.6439                                                   APP05370
      V2A(5,6)=0.5140                                                   APP05380
      V2A(5,7)=0.3569                                                   APP05390
      V2A(5,8)=0.1865                                                   APP05400
      V2A(5,9)=0.0950                                                   APP05410
      V2A(5,10)=0.0000                                                  APP05420
C                                                                       APP05430
C     ... CONTINUE FOR R=.6R                                            APP05440
C                                                                       APP05450
      V1F(6,1)=0.0000                                                   APP05460
      V1F(6,2)=0.0000                                                   APP05470
      V1F(6,3)=0.0000                                                   APP05480
      V1F(6,4)=0.0000                                                   APP05490
      V1F(6,5)=0.0000                                                   APP05500
      V1F(6,6)=0.0000                                                   APP05510
      V1F(6,7)=0.0006                                                   APP05520
      V1F(6,8)=0.0022                                                   APP05530
      V1F(6,9)=0.0067                                                   APP05540
      V1F(6,10)=0.0169                                                  APP05550
      V1F(6,11)=0.0382                                                  APP05560
      V1A(6,1)=0.0000                                                   APP05570
      V1A(6,2)=0.0000                                                   APP05580
      V1A(6,3)=0.0000                                                   APP05590
      V1A(6,4)=0.0000                                                   APP05600
      V1A(6,5)=0.0000                                                   APP05610
      V1A(6,6)=0.0000                                                   APP05620
      V1A(6,7)=0.0000                                                   APP05630
      V1A(6,8)=0.0000                                                   APP05640
      V1A(6,9)=0.0000                                                   APP05650
      V1A(6,10)=0.0000                                                  APP05660
      V2F(6,1)=1.0000                                                   APP05670
      V2F(6,2)=0.9690                                                   APP05680
      V2F(6,3)=0.8790                                                   APP05690
      V2F(6,4)=0.8090                                                   APP05700
      V2F(6,5)=0.7200                                                   APP05710
      V2F(6,6)=0.6060                                                   APP05720
      V2F(6,7)=0.4620                                                   APP05730
      V2F(6,8)=0.3775                                                   APP05740
      V2F(6,9)=0.2720                                                   APP05750
      V2F(6,10)=0.1485                                                  APP05760
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      V2F(6,11)=0.0000                                                   APP05770
      V2A(6,1)=1.0000                                                    APP05780
      V2A(6,2)=0.9613                                                    APP05790
      V2A(6,3)=0.8426                                                    APP05800
      V2A(6,4)=0.7530                                                    APP05810
      V2A(6,5)=0.6415                                                    APP05820
      V2A(6,6)=0.5110                                                    APP05830
      V2A(6,7)=0.3585                                                    APP05840
      V2A(6,8)=0.1885                                                    APP05850
      V2A(6,9)=0.0965                                                    APP05860
      V2A(6,10)=0.0000                                                   APP05870
C                                                                        APP05880
C     ... CONTINUE FOR R=.7R                                             APP05890
C                                                                        APP05900
      V1F(7,1)=0.0000                                                    APP05910
      V1F(7,2)=0.0000                                                    APP05920
      V1F(7,3)=0.0000                                                    APP05930
      V1F(7,4)=0.0000                                                    APP05940
      V1F(7,5)=0.0000                                                    APP05950
      V1F(7,6)=0.0000                                                    APP05960
      V1F(7,7)=0.0000                                                    APP05970
      V1F(7,8)=0.0000                                                    APP05980
      V1F(7,9)=0.0000                                                    APP05990
      V1F(7,10)=0.0000                                                   APP06000
      V1F(7,11)=0.0000                                                   APP06010
      V1A(7,1)=0.0000                                                    APP06020
      V1A(7,2)=0.0000                                                    APP06030
      V1A(7,3)=0.0000                                                    APP06040
      V1A(7,4)=0.0000                                                    APP06050
      V1A(7,5)=0.0000                                                    APP06060
      V1A(7,6)=0.0000                                                    APP06070
      V1A(7,7)=0.0000                                                    APP06080
      V1A(7,8)=0.0000                                                    APP06090
      V1A(7,9)=0.0000                                                    APP06100
      V1A(7,10)=0.0000                                                   APP06110
      V2F(7,1)=1.0000                                                    APP06120
      V2F(7,2)=0.9675                                                    APP06130
      V2F(7,3)=0.8660                                                    APP06140
      V2F(7,4)=0.7850                                                    APP06150
      V2F(7,5)=0.6840                                                    APP06160
      V2F(7,6)=0.5615                                                    APP06170
      V2F(7,7)=0.4140                                                    APP06180
      V2F(7,8)=0.3300                                                    APP06190
      V2F(7,9)=0.2337                                                    APP06200
      V2F(7,10)=0.1240                                                   APP06210
      V2F(7,11)=0.0000                                                   APP06220
      V2A(7,1)=1.0000                                                    APP06230
      V2A(7,2)=0.9600                                                    APP06240
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      V2A(7,3)=0.8400                                                   APP06250
      V2A(7,4)=0.7500                                                   APP06260
      V2A(7,5)=0.6400                                                   APP06270
      V2A(7,6)=0.5100                                                   APP06280
      V2A(7,7)=0.3600                                                   APP06290
      V2A(7,8)=0.1900                                                   APP06300
      V2A(7,9)=0.0975                                                   APP06310
      V2A(7,10)=0.0000                                                  APP06320
C                                                                       APP06330
C     ... CONTINUE FOR R=.8R                                            APP06340
C                                                                       APP06350
      V1F(8,1)=0.0000                                                   APP06360
      V1F(8,2)=0.0000                                                   APP06370
      V1F(8,3)=0.0000                                                   APP06380
      V1F(8,4)=0.0000                                                   APP06390
      V1F(8,5)=0.0000                                                   APP06400
      V1F(8,6)=0.0000                                                   APP06410
      V1F(8,7)=0.0000                                                   APP06420
      V1F(8,8)=0.0000                                                   APP06430
      V1F(8,9)=0.0000                                                   APP06440
      V1F(8,10)=0.0000                                                  APP06450
      V1F(8,11)=0.0000                                                  APP06460
      V1A(8,1)=0.0000                                                   APP06470
      V1A(8,2)=0.0000                                                   APP06480
      V1A(8,3)=0.0000                                                   APP06490
      V1A(8,4)=0.0000                                                   APP06500
      V1A(8,5)=0.0000                                                   APP06510
      V1A(8,6)=0.0000                                                   APP06520
      V1A(8,7)=0.0000                                                   APP06530
      V1A(8,8)=0.0000                                                   APP06540
      V1A(8,9)=0.0000                                                   APP06550
      V1A(8,10)=0.0000                                                  APP06560
      V2F(8,1)=1.0000                                                   APP06570
      V2F(8,2)=0.9635                                                   APP06580
      V2F(8,3)=0.8520                                                   APP06590
      V2F(8,4)=0.7635                                                   APP06600
      V2F(8,5)=0.6545                                                   APP06610
      V2F(8,6)=0.5265                                                   APP06620
      V2F(8,7)=0.3765                                                   APP06630
      V2F(8,8)=0.2925                                                   APP06640
      V2F(8,9)=0.2028                                                   APP06650
      V2F(8,10)=0.1050                                                  APP06660
      V2F(8,11)=0.0000                                                  APP06670
      V2A(8,1)=1.0000                                                   APP06680
      V2A(8,2)=0.9600                                                   APP06690
      V2A(8,3)=0.8400                                                   APP06700
      V2A(8,4)=0.7500                                                   APP06710
      V2A(8,5)=0.6400                                                   APP06720
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      V2A(8,6)=0.5100                                               APP06730
      V2A(8,7)=0.3600                                               APP06740
      V2A(8,8)=0.1900                                               APP06750
      V2A(8,9)=0.0975                                               APP06760
      V2A(8,10)=0.0000                                              APP06770
C                                                                   APP06780
C     ... CONTINUE FOR R=.9R                                        APP06790
C                                                                   APP06800
      V1F(9,1)=0.0000                                               APP06810
      V1F(9,2)=0.0000                                               APP06820
      V1F(9,3)=0.0000                                               APP06830
      V1F(9,4)=0.0000                                               APP06840
      V1F(9,5)=0.0000                                               APP06850
      V1F(9,6)=0.0000                                               APP06860
      V1F(9,7)=0.0000                                               APP06870
      V1F(9,8)=0.0000                                               APP06880
      V1F(9,9)=0.0000                                               APP06890
      V1F(9,10)=0.0000                                              APP06900
      V1F(9,11)=0.0000                                              APP06910
      V1A(9,1)=0.0000                                               APP06920
      V1A(9,2)=0.0000                                               APP06930
      V1A(9,3)=0.0000                                               APP06940
      V1A(9,4)=0.0000                                               APP06950
      V1A(9,5)=0.0000                                               APP06960
      V1A(9,6)=0.0000                                               APP06970
      V1A(9,7)=0.0000                                               APP06980
      V1A(9,8)=0.0000                                               APP06990
      V1A(9,9)=0.0000                                               APP07000
      V1A(9,10)=0.0000                                              APP07010
      V2F(9,1)=1.0000                                               APP07020
      V2F(9,2)=0.9600                                               APP07030
      V2F(9,3)=0.8400                                               APP07040
      V2F(9,4)=0.7500                                               APP07050
      V2F(9,5)=0.6400                                               APP07060
      V2F(9,6)=0.5100                                               APP07070
      V2F(9,7)=0.3600                                               APP07080
      V2F(9,8)=0.2775                                               APP07090
      V2F(9,9)=0.1900                                               APP07100
      V2F(9,10)=0.0975                                              APP07110
      V2F(9,11)=0.0000                                              APP07120
      V2A(9,1)=1.0000                                               APP07130
      V2A(9,2)=0.9600                                               APP07140
      V2A(9,3)=0.8400                                               APP07150
      V2A(9,4)=0.7500                                               APP07160
      V2A(9,5)=0.6400                                               APP07170
      V2A(9,6)=0.5100                                               APP07180
      V2A(9,7)=0.3600                                               APP07190
      V2A(9,8)=0.1900                                               APP07200
```

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      V2A(9,9)=0.0975                                                   APP07210
      V2A(9,10)=0.0000                                                  APP07220
C                                                                       APP07230
C     ... CONTINUE FOR R=1.0R                                           APP07240
C                                                                       APP07250
      V1F(10,1)=0.0000                                                  APP07260
      V1F(10,2)=0.0000                                                  APP07270
      V1F(10,3)=0.0000                                                  APP07280
      V1F(10,4)=0.0000                                                  APP07290
      V1F(10,5)=0.0000                                                  APP07300
      V1F(10,6)=0.0000                                                  APP07310
      V1F(10,7)=0.0000                                                  APP07320
      V1F(10,8)=0.0000                                                  APP07330
      V1F(10,9)=0.0000                                                  APP07340
      V1F(10,10)=0.0000                                                 APP07350
      V1F(10,11)=0.0000                                                 APP07360
      V1A(10,1)=0.0000                                                  APP07370
      V1A(10,2)=0.0000                                                  APP07380
      V1A(10,3)=0.0000                                                  APP07390
      V1A(10,4)=0.0000                                                  APP07400
      V1A(10,5)=0.0000                                                  APP07410
      V1A(10,6)=0.0000                                                  APP07420
      V1A(10,7)=0.0000                                                  APP07430
      V1A(10,8)=0.0000                                                  APP07440
      V1A(10,9)=0.0000                                                  APP07450
      V1A(10,10)=0.0000                                                 APP07460
      V2F(10,1)=1.0000                                                  APP07470
      V2F(10,2)=0.9600                                                  APP07480
      V2F(10,3)=0.8400                                                  APP07490
      V2F(10,4)=0.7500                                                  APP07500
      V2F(10,5)=0.6400                                                  APP07510
      V2F(10,6)=0.5100                                                  APP07520
      V2F(10,7)=0.3600                                                  APP07530
      V2F(10,8)=0.2775                                                  APP07540
      V2F(10,9)=0.1900                                                  APP07550
      V2F(10,10)=0.0975                                                 APP07560
      V2F(10,11)=0.0000                                                 APP07570
      V2A(10,1)=1.0000                                                  APP07580
      V2A(10,2)=0.9600                                                  APP07590
      V2A(10,3)=0.8400                                                  APP07600
      V2A(10,4)=0.7500                                                  APP07610
      V2A(10,5)=0.6400                                                  APP07620
      V2A(10,6)=0.5100                                                  APP07630
      V2A(10,7)=0.3600                                                  APP07640
      V2A(10,8)=0.1900                                                  APP07650
      V2A(10,9)=0.0975                                                  APP07660
      V2A(10,10)=0.0000                                                 APP07670
C                                                                       APP07680
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C        CALCULATE BLADE SECTION PROPERTIES ALONG PROPELLER BLADE RADIUS    APP07690
C        AT:                R                    IR                         APP07700
C                     .167R OR .18R               1                         APP07710
C                     .20R                        2                         APP07720
C                     .30R                        3                         APP07730
C                     .40R                        4                         APP07740
C                     .50R                        5                         APP07750
C                     .60R                        6                         APP07760
C                     .70R                        7                         APP07770
C                     .80R                        8                         APP07780
C                     .90R                        9                         APP07790
C                    1.00R                       10                         APP07800
C                                                                           APP07810
         DO 52 IR=1,10                                                      APP07820
CC                                                                          APP07830
CC           ... INITIALIZE SUMMATION VARIABLES TO ZERO FOR EACH ITERATIONAPP07840
CC                                                                          APP07850
             SUMAA=0.0                                                      APP07860
             SUMAXA=0.0                                                     APP07870
             SUMAYA=0.0                                                     APP07880
             SMAX2A=0.0                                                     APP07890
             SMAY2A=0.0                                                     APP07900
             SUMAF=0.0                                                      APP07910
             SUMAXF=0.0                                                     APP07920
             SUMAYF=0.0                                                     APP07930
             SMAX2F=0.0                                                     APP07940
             SMAY2F=0.0                                                     APP07950
             DLFASM=0.0                                                     APP07960
             DLFFSM=0.0                                                     APP07970
CC                                                                          APP07980
CC           ... BEGIN WITH "AFT" PORTION (P=0 TO P=-1) OF BLADE SECTION    APP07990
CC           AS DEPICTED IN FIGURE (1), REF 2                               APP08000
CC                                                                          APP08010
             DO 21 I=1,9                                                    APP08020
                 IP1=I+1                                                    APP08030
                 YFACE(I)=(V1A(IR,I))*(TR(IR)-(0.1*TR(IR)))                 APP08040
                 YBACK(I)=((V1A(IR,I)+V2A(IR,I))*(TR(IR)-(0.1*TR(IR)))      APP08050
     1                   +(0.1*TR(IR))                                      APP08060
                 HA(I)=YBACK(I)-YFACE(I)                                    APP08070
                 Y(I)=(YBACK(I)+YFACE(I))/2.0                               APP08080
                 YFACE(IP1)=(V1A(IR,IP1))*(TR(IR)-(0.1*TR(IR)))             APP08090
                 YBACK(IP1)=((V1A(IR,IP1)+V2A(IR,IP1))                      APP08100
     1                   *(TR(IR)-(0.1*TR(IR))))+(0.1*TR(IR))               APP08110
                 HA(IP1)=YBACK(IP1)-YFACE(IP1)                              APP08120
                 Y(IP1)=(YBACK(IP1)+YFACE(IP1))/2.0                         APP08130
                 IF(.NOT.((I.EQ.1).OR.(I.EQ.2)))GO TO 18                    APP08140
                     DELPA(I)=(PLA(IR)/10.0)*2.0                            APP08150
                 GO TO 20                                                   APP08160
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18          CONTINUE                                                      APP08170
            IF(.NOT.((I.EQ.8).OR.(I.EQ.9)))GO TO 19                       APP08180
                  DELPA(I)=(PLA(IR)/10.0)*0.5                             APP08190
            GO TO 20                                                      APP08200
19          CONTINUE                                                      APP08210
                  DELPA(I)=(PLA(IR)/10.0)*1.0                             APP08220
20          CONTINUE                                                      APP08230
            AA(I)=(0.5*(HA(IP1)+HA(I)))*DELPA(I)                          APP08240
            DLPASM=DLPASM+DELPA(I)                                        APP08250
            XA(I)=DLPASM-(DELPA(I)/2.0)                                   APP08260
            YA(I)=(Y(IP1)+Y(I))/2.0                                       APP08270
            SUMAA=SUMAA+AA(I)                                             APP08280
            SUMAXA=SUMAXA+(AA(I)*XA(I))                                   APP08290
            SUMAYA=SUMAYA+(AA(I)*YA(I))                                   APP08300
            SMAX2A=SMAX2A+(AA(I)*((XA(I))**2))+                           APP08310
     1           ((1.0/12.0)*((HA(I)+HA(IP1))/2.0)*(DELPA(I)**3))         APP08320
            SMAY2A=SMAY2A+(AA(I)*((YA(I))**2))+                           APP08330
     1         ((1.0/12.0)*(DELPA(I))*(((HA(I)+HA(IP1))/2.0)**3))         APP08340
21      CONTINUE                                                          APP08350
CC                                                                        APP08360
CC      ...CONTINUE WITH "FORWARD" PORTION (P=0 TO P=+1) OF BLADE         APP08370
CC      SECTION AS DEPICTED IN FIGURE (1), REF 2                          APP08380
CC                                                                        APP08390
        DO 25 I=1,10                                                      APP08400
            IP1=I+1                                                       APP08410
            YFACE(I)=(V1F(IR,I))*(TR(IR)-(0.1*TR(IR)))                    APP08420
            YBACK(I)=((V1F(IR,I)+V2F(IR,I))*(TR(IR)-(0.1*TR(IR))))        APP08430
     1               +(0.1*TR(IR))                                        APP08440
            HF(I)=YBACK(I)-YFACE(I)                                       APP08450
            Y(I)=(YBACK(I)+YFACE(I))/2.0                                  APP08460
            YFACE(IP1)=(V1F(IR,IP1))*(TR(IR)-(0.1*TR(IR)))                APP08470
            YBACK(IP1)=((V1F(IR,IP1)+V2F(IR,IP1))                         APP08480
     1               *(TR(IR)-(0.1*TR(IR))))+(0.1*TR(IR))                 APP08490
            HF(IP1)=YBACK(IP1)-YFACE(IP1)                                 APP08500
            Y(IP1)=(YBACK(IP1)+YFACE(IP1))/2.0                            APP08510
            IF(.NOT.((I.EQ.1).OR.(I.EQ.2)))GO TO 22                       APP08520
                  DELPF(I)=(PLF(IR)/10.0)*2.0                             APP08530
            GO TO 24                                                      APP08540
22          CONTINUE                                                      APP08550
            IF(.NOT.((I.EQ.7).OR.(I.EQ.8).OR.(I.EQ.9).OR.(I.EQ.10)))      APP08560
     1      GO TO 23                                                      APP08570
                  DELPF(I)=(PLF(IR)/10.0)*0.5                             APP08580
            GO TO 24                                                      APP08590
23          CONTINUE                                                      APP08600
                  DELPF(I)=(PLF(IR)/10.0)*1.0                             APP08610
24          CONTINUE                                                      APP08620
            AF(I)=(0.5*(HF(IP1)+HF(I)))*DELPF(I)                          APP08630
            DLPFSM=DLPFSM+DELPF(I)                                        APP08640
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            XF(I)=DLPFSM-(DELPF(I)/2.0)                                 APP08650
            YF(I)=(Y(IP1)+Y(I))/2.0                                     APP08660
            SUMAF=SUMAF+AF(I)                                           APP08670
            SUMAXF=SUMAXF+(AF(I)*XF(I))                                 APP08680
            SUMAYF=SUMAYF+(AF(I)*YF(I))                                 APP08690
            SMAX2F=SMAX2F+(AF(I)*((XF(I))**2))+                         APP08700
     1           ((1.0/12.0)*((HF(I)+HF(IP1))/2.0)*(DELPF(I)**3))       APP08710
            SMAY2F=SMAY2F+(AF(I)*((YF(I))**2))+                         APP08720
     1         ((1.0/12.0)*(DELPF(I))*(((HF(I)+HF(IP1))/2.0)**3))       APP08730
   25     CONTINUE                                                      APP08740
CC                                                                      APP08750
CC        DETERMINE BLADE SECTION PROPERTIES, I.E., CROSS-SECTION AREA, APP08760
CC        AND AREA CENTROID LOCATION WITH RESPECT TO PITCH-REFERENCE    APP08770
CC        LINE AND LINE OF MAXIMUM BLADE SECTION THICKNESS AS DEPICTED  APP08780
CC        IN FIGURE (1), REF 2                                          APP08790
CC                                                                      APP08800
          AREA(IR)=SUMAA+SUMAF                                          APP08810
          IF(.NOT.(AREA(IR).LE.0.0))GO TO 26                            APP08820
              XMT(IR)=0.0                                               APP08830
              YPRL(IR)=(DIA*(0.0030))/2.0                               APP08840
          GO TO 27                                                      APP08850
   26     CONTINUE                                                      APP08860
              XMT(IR)=((SUMAXF)-(SUMAXA))/AREA(IR)                      APP08870
              YPRL(IR)=((SUMAYF)+(SUMAYA))/AREA(IR)                     APP08880
   27     CONTINUE                                                      APP08890
CC                                                                      APP08900
CC        CALCULATE MOMENT OF INERTIA WITH RESPECT TO NEUTRAL AXES      APP08910
CC        USING PARALLEL AXIS THEOREM                                   APP08920
CC                                                                      APP08930
          RIYYNA(IR)=((SMAX2F)+(SMAX2A))-                               APP08940
     1               (((XMT(IR))**2)*AREA(IR))                          APP08950
          RIXXNA(IR)=((SMAY2F)+(SMAY2A))-                               APP08960
     1               (((YPRL(IR))**2)*AREA(IR))                         APP08970
CC                                                                      APP08980
CC        DETERMINE LOCATION OF "CG" (I.E., NEUTRAL AXES ORIGIN) WITH   APP08990
CC        RESPECT TO PITCH-REFERENCE LINE AND GENERATOR LINE DEPICTED   APP09000
CC        IN FIGURE (1), REF2                                           APP09010
CC                                                                      APP09020
          IF(.NOT.(XMT(IR).LT.0.0))GO TO 28                             APP09030
              DN=BR(IR)+ABS(XMT(IR))                                    APP09040
          GO TO 30                                                      APP09050
   28     CONTINUE                                                      APP09060
          IF(.NOT.(XMT(IR).GT.0.0))GO TO 29                             APP09070
              DN=BR(IR)-ABS(XMT(IR))                                    APP09080
          GO TO 30                                                      APP09090
   29     CONTINUE                                                      APP09100
              DN=BR(IR)                                                 APP09110
   30     CONTINUE                                                      APP09120
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      IF(.NOT.(DN.LT.AR(IR)))GO TO 31
          XCG(IR)=AR(IR)-DN
      GO TO 33
31    CONTINUE
      IF(.NOT.(DN.GT.AR(IR)))GO TO 32
          XCG(IR)=-(DN-AR(IR))
      GO TO 33
32    CONTINUE
          XCG(IR)=0.0
33    CONTINUE
      YCG(IR)=YPRL(IR)
CC
CC    DETERMINE "CRITICAL POINTS" OF A BLADE SECTION WITH RESPECT
CC    TO NEUTRAL AXES WHERE STRESSES ARE LIKELY TO BE A MAXIMUM
CC
CC    ...CALCULATE ORDINATE (U2) AND ABCISSA (W2) OF CRITICAL POINT
CC    NO. 2 DEPICTED IN FIGURE (10), REF 8
CC
      W2(IR)=(AR(IR)-BR(IR))-XCG(IR)
      U2(IR)=(((V1A(IR,1)+V2A(IR,1))*(TR(IR)-(0.1*TR(IR))))+
     1       (0.1*TR(IR)))-YPRL(IR)
CC
CC    ...CALCULATE ORDINATE (U4) AND ABCISSA (W4) OF CRITICAL POINT
CC    NO. 4 DEPICTED IN FIGURE (10), REF 8
CC
      W4(IR)=W2(IR)
      U4(IR)=((V1A(IR,1))*(TR(IR)-(0.1*TR(IR))))-YPRL(IR)
CC
CC    ...CALCULATE ORDINATE (U1) AND ABCISSA (W1) OF CRITICAL POINT
CC    NO. 1 DEPICTED IN FIGURE (10), REF 8
CC
      W1(IR)=-((CR(IR)-AR(IR))+XCG(IR))
      YBK=(V1A(IR,10)+V2A(IR,10))*(TR(IR)-(0.1*TR(IR)))
      YFC=(V1A(IR,10))*(TR(IR)-(0.1*TR(IR)))
      IF(.NOT.(YCG(IR).GT.YBK))GO TO 40
          U1(IR)=YFC-YCG(IR)
      GO TO 45
40    CONTINUE
      IF(.NOT.((YCG(IR).LE.YBK).AND.(YCG(IR).GE.YFC)))GO TO 44
          IF(.NOT.((ABS(YCG(IR)-YFC)).GT.(ABS(YBK-YCG(IR)))))
     1    GO TO 41
              U1(IR)=YFC-YCG(IR)
          GO TO 43
41        CONTINUE
          IF(.NOT.((ABS(YCG(IR)-YFC)).LT.(ABS(YBK-YCG(IR)))))
     1    GO TO 42
              U1(IR)=YBK-YCG(IR)
          GO TO 43
```

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 42          CONTINUE                                                 APP09610
                U1(IR)=0.0                                            APP09620
 43          CONTINUE                                                 APP09630
          GO TO 45                                                    APP09640
 44       CONTINUE                                                    APP09650
             U1(IR)=YBK-YCG(IR)                                       APP09660
 45       CONTINUE                                                    APP09670
CC                                                                    APP09680
CC        ...CALCULATE ORDINATE (U3) AND ABCISSA (W3) OF CRITICAL POINTAPP09690
CC        NO. 3 DEPICTED IN FIGURE (10), REF 8                        APP09700
CC                                                                    APP09710
          W3(IR)=CR(IR)-ABS(W1(IR))                                   APP09720
          YBK=(V1F(IR,11)+V2F(IR,11))*(TR(IR)-(0.1*TR(IR)))           APP09730
          YFC=(V1F(IR,11))*(TR(IR)-(0.1*TR(IR)))                      APP09740
          IF(.NOT.(YCG(IR).GT.YBK))GO TO 46                           APP09750
             U3(IR)=YFC-YCG(IR)                                       APP09760
          GO TO 51                                                    APP09770
 46       CONTINUE                                                    APP09780
          IF(.NOT.((YCG(IR).LE.YBK).AND.(YCG(IR).GE.YFC)))GO TO 50    APP09790
             IF(.NOT.((ABS(YCG(IR)-YFC)).GT.(ABS(YBK-YCG(IR)))))      APP09800
     1       GO TO 47                                                 APP09810
                U3(IR)=YFC-YCG(IR)                                    APP09820
             GO TO 49                                                 APP09830
 47          CONTINUE                                                 APP09840
             IF(.NOT.((ABS(YCG(IR)-YFC)).LT.(ABS(YBK-YCG(IR)))))      APP09850
     1       GO TO 48                                                 APP09860
                U3(IR)=YBK-YCG(IR)                                    APP09870
             GO TO 49                                                 APP09880
 48          CONTINUE                                                 APP09890
                U3(IR)=0.0                                            APP09900
 49          CONTINUE                                                 APP09910
          GO TO 51                                                    APP09920
 50       CONTINUE                                                    APP09930
             U3(IR)=YBK-YCG(IR)                                       APP09940
 51       CONTINUE                                                    APP09950
 52 CONTINUE                                                          APP09960
    RETURN                                                            APP09970
    END                                                               APP09980
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      SUBROUTINE BLDVOL(VOLBLD)                                         APP1C010
C                                                                       APP1C020
C                                                                       APP1C030
C     SUBROUTINE:  BLDVOL                    DATE OF LAST REVISION: APR 83 APP1C040
C                                                                       APP1C050
C     INPUT              OUTPUT              DEFINITION                 APP1C060
C                                                                       APP1C070
C     DIA                                    PROPELLER DIAMETER (FEET)  APP1C080
C     Z                                      NO. OF PROPELLER BLADES    APP1C090
C     COMMON/AREBLD/                         BLADE SECTION AREAS (FEET**2) APP1C100
C                        VOLBLD              PROPELLER BLADE VOLUME     APP1C110
C                                            (FEET**3)                  APP1C120
C                                                                       APP1C130
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,             APP1C140
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,    APP1C150
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,                              APP1C160
     3        VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,              APP1C170
     4        PWATVA,PROMAT,DIALIM,ETARR,                               APP1C180
     5        RJ,C75R,R75R,KT,KQ                                        APP1C190
      REAL*4  AREA(10),WIDTH,VOL1,VOL2,VOLBLD                           APP1C200
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP1C210
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP1C220
     2AEAOCV,TCSTRS,RJ                                                  APP1C230
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP1C240
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP1C250
      COMMON /AREBLD/AREA                                               APP1C260
C                                                                       APP1C270
C     DETERMINE BLADE VOLUME BY SIMPSON INTEGRATION SCHEME OF BLADE     APP1C280
C     CROSS-SECTIONAL AREAS FROM 2/10 RADIUS OUTWARD TO TIP             APP1C290
C                                                                       APP1C300
      VOL1=(((DIA/2.0)*0.1)/3.0)*(AREA(2)+(4.0*AREA(3))+(2.0*AREA(4))+  APP1C310
     1                               (4.0*AREA(5))+(2.0*AREA(6))+       APP1C320
     2                               (4.0*AREA(7))+(2.0*AREA(8))+       APP1C330
     3                               (4.0*AREA(9))+AREA(10))            APP1C340
C                                                                       APP1C350
C     DETERMINE BLADE VOLUME FROM 2/10 RADIUS INWARD TO R=.18R FOR 3 & 7APP1C360
C     BLADE PROPELLERS OR R=.167R FOR 4,5,&6 BLADE PROPELLERS USING     APP1C370
C     SIMPLE TRAPEZOIDAL INTEGRATION SCHEME                             APP1C380
C                                                                       APP1C390
      IF(.NOT.(Z.EQ.3.0))GO TO 1                                        APP1C400
         WIDTH=(DIA/2.0)*(0.2-0.18)                                     APP1C410
      GO TO 5                                                           APP1C420
    1 CONTINUE                                                          APP1C430
      IF(.NOT.(Z.EQ.4.0))GO TO 2                                        APP1C440
         WIDTH=(DIA/2.0)*(0.2-0.167)                                    APP1C450
      GO TO 5                                                           APP1C460
    2 CONTINUE                                                          APP1C470
      IF(.NOT.(Z.EQ.5.0))GO TO 3                                        APP1C480
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      WIDTH=(DIA/2.0)*(0.2-0.167)                                      APP1C490
    GO TO 5                                                            APP1C500
  3 CONTINUE                                                           APP1C510
    IF(.NOT.(Z.EQ.6.0))GO TO 4                                         APP1C520
      WIDTH=(DIA/2.0)*(0.2-0.167)                                      APP1C530
    GO TO 5                                                            APP1C540
  4 CONTINUE                                                           APP1C550
      WIDTH=(DIA/2.0)*(0.2-0.18)                                       APP1C560
  5 CONTINUE                                                           APP1C570
    VOL2=((AREA(1)+AREA(2))/2.0)*WIDTH                                 APP1C580
C                                                                      APP1C590
C   CALCULATE PROPELLER BLADE VOLUME                                   APP1C600
C                                                                      APP1C610
    VOLBLD=VOL1+VOL2                                                   APP1C620
    RETURN                                                             APP1C630
    END                                                                APP1C640
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      SUBROUTINE ELPOW1(KT,SOWBAL)
C
C
C     SUBROUTINE: BLPOW1                  DATE OF LAST REVISION: FEB 83
C
C     INPUT          OUTPUT               DEFINITION
C
C     PE                                  HULL EFFECTIVE HORSEPOWER(HP)
C     KT                                  THRUST COEFFICIENT
C     DIA                                 PROPELLER DIAMETER (FT)
C     N                                   PROPELLER REVOLUTION RATE(RPM
C     WATRO                               WATER DENSITY (LBF-SEC2/FT4)
C     V                                   SHIP SPEED (FT/SEC)
C     WT                                  WAKE FRACTION
C     TD                                  THRUST DEDUCTION
C     ETARR                               RELATIVE ROTATIVE EFFICIENCY
C                    SOWBAL               CONSTRAINT VARIABLE FOR PRO-
C                                         PELLER-DEVELOPED EFFECTIVE
C                                         HORSEPOWER CONSTRAINT
C                                         (SOWBAL<0)
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       KT,PEDEV,THRST,PT,SOWBAL
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE THRUST DEVELOPED BY EACH PROPELLER
C
      THRST=(KT*WATRO*(DIA**4)*((N/60.0)**2))
C
C     DETERMINE HULL EFFECTIVE POWER DEVELOPED BY PROPELLER(S)
C
      PT=(THRST*((1.0-WT)*V))/550.0
      PEDEV=((((1.0-TD)/(1.0-WT))*ETARR*PT)*NCSCRW)
C
C     CALCULATE CONSTRAINT VARIABLE
C
      SOWBAL=1.0-(PEDEV/PE)
      RETURN
      END
```

```
      SUBROUTINE ELPOW2(KQ,SOWBAL)
C
C     SUBROUTINE: BLPOW2                          DATE OF LAST REVISION: FEB 83
C
C     INPUT            OUTPUT                     DEFINITION
C
C     QS                                          DELIVERED TORQUE (FT-LBF)
C     KQ                                          TORQUE COEFFICIENT
C     DIA                                         PROPELLER DIAMETER (FT)
C     N                                           PROPELLER REVOLUTION RATE(RPM
C     WATRO                                       WATER DENSITY (LBF-SEC2/FT4)
C                      SOWBAL                     CONSTRAINT VARIABLE FOR PRO-
C                                                 PELLER REQUIRED TORQUE
C                                                 (SOWBAL<0)
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,
     5       KQ,QSABD,SOWBAL
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE THE TORQUE ABSORBED BY PROPELLER
C
      QSABD=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
C
C     CALCULATE CONSTRAINT VARIABLE
C
      SOWBAL=1.0-(QSABD/QS)
      RETURN
      END
```

```
      SUBROUTINE BLPCW3(KT,KQ,SOWBLP,SOWBLQ)
C
C
C     SUBROUTINE: BLPCW3                       DATE OF LAST REVISION: FEB 83
C
C     INPUT             OUTPUT                 DEFINITION
C
C     KT                                       THRUST COEFFICIENT
C     KQ                                       TORQUE COEFFICIENT
C     PE                                       HULL EFFECTIVE HORSEPOWER(HP)
C     N                                        PROPELLER REVOLUTION RATE(RPM
C     QS                                       DELIVERED TORQUE (FT-LBF)
C     NOSCRW                                   NUMBER OF PROPELLERS
C     WT                                       WAKE FRACTION
C     TD                                       THRUST DEDUCTION
C     ETARR                                    RELATIVE ROTATIVE EFFICIENCY
C                       SOWBLP                 CONSTRAINT VARIABLE FOR
C                                              EFFECTIVE HORSEPOWER
C                                              CONSTRAINT (SOWBLP<0)
C                       SOWBLQ                 CONSTRAINT VARIABLE FOR
C                                              DELIVERED POWER
C                                              CONSTRAINT (SOWBLQ<0)
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,KT,KQ,
     5       PII,ETAOSP,THRST,PEDEV,QPABD,PDABD,PD,SOWBLP,SOWBLQ
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
      PII=3.141592654
C
C     CALCULATE THRUST DEVELOPED BY EACH PROPELLER
C
      THRST=(KT*WATRO*(DIA**4)*((N/60.0)**2))
C
C     DETERMINE  EFFECTIVE POWER DEVELOPED BY PROPELLER(S)
C
      PT=(THRST*((1.0-WT)*V))/550.0
      PEDEV=((((1.0-TD)/(1.0-WT))*ETARR*PT)*NOSCRW)
C
C     CALCULATE THE TORQUE ABSORBED BY PROPELLER
C
      QPABD=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
```

```
C
C     CALCULATE THE POWER ABSORBED BY THE PROPELLER
C
      PDABD=(2.0*PII*QPABD*N)/33000.0
C
C     CALCULATE THE POWER DELIVERED TO THE PROPELLER
C
      PD=(2.0*PII*QS*N)/33000.0
C
C     DETERMINE CONSTRAINT VARIABLES
C
      SOWBLP=1.0-(PEDEV/PE)
      SOWBLC=(PDAED/PD)-1.0
      RETURN
      END
```

```
      SUBROUTINE CALCKQ(J,PDIVD,AEDVAO,Z,REYNO,KQ)                      APP12190
C                                                                       APP12200
C     SUBROUTINE: CALCKQ                      DATE OF LAST REVISION: FEB 83APP12210
C                                                                       APP12220
C     INPUT           OUTPUT                  DEFINITION                APP12230
C                                                                       APP12240
C     AEDVAO                                  EXPANDED AREA RATIO       APP12250
C     PDIVD                                   PITCH-DIAMETER RATIO      APP12260
C     Z                                       NO. OF BLADES             APP12270
C     J                                       ADAVNCE RATIO             APP12280
C     REYNO                                   REYNOLD'S NO. 3/4 RADIUS  APP12290
C                                             (CORRECTED FOR T/C 3/4 RADIUSAPP12300
C                     KQ                      THRUST COEFFICIENT        APP12310
C                                                                       APP12320
      REAL*4 J,PDIVD,AEDVAO,Z,REYNO,KQ,KQ1,KQ2,KQ3,KQ4,KQ5,KQ6,KQ7,KQ8, APP12330
     1       KQ9,KQ10,DELKQ,DELKQ1,DELKQ2,DELKQ3,REYFAC                 APP12340
C                                                                       APP12350
C     FIRST, CALCULATING "KQ1" THRU "KQ10".....                         APP12360
C                                                                       APP12370
      KQ1=(.00379368)+((.00886523)*(J**2))+((-.032241)*J*PDIVD)+        APP12380
     1    ((.00344778)*(PDIVD**2))+((-.0408811)*PDIVD*AEDVAO)           APP12390
      KQ2=((-.108009)*J*PDIVD*AEDVAO)+((-.0885381)*(J**2)*PDIVD*AEDVAO)+APP12400
     1    ((.188561)*(PDIVD**2)*AEDVAO)+((-.00370871)*J*Z)+             APP12410
     2    ((.00513696)*PDIVD*Z)                                         APP12420
      KQ3=((.0209449)*J*PDIVD*Z)+((.00474319)*(J**2)*PDIVD*Z)+          APP12430
     1    ((-.00723408)*(J**2)*AEDVAO*Z)+((.00438388)*J*PDIVD*AEDVAO*Z)+APP12440
     2    ((-.0269403)*(PDIVD**2)*AEDVAO*Z)                             APP12450
      KQ4=((.0558082)*(J**3)*AEDVAO)+((.0161886)*(PDIVD**3)*AEDVAO)+    APP12460
     1    ((.00318086)*J*(PDIVD**3)*AEDVAO)+((.015896)*(AEDVAO**2))+    APP12470
     2    ((.0471729)*J*(AEDVAO**2))                                    APP12480
      KQ5=((.0196283)*(J**3)*(AEDVAO**2))+((-.0502782)*PDIVD*           APP12490
     1    (AEDVAO**2))+((-.030055)*(J**3)*PDIVD*(AEDVAO**2))+           APP12500
     2    ((.0417122)*(J**2)*(PDIVD**2)*(AEDVAO**2))+                   APP12510
     3    ((-.0397722)*(PDIVD**3)*(AEDVAO**2))                          APP12520
      KQ6=((-.00350024)*(PDIVD**6)*(AEDVAO**2))+((-.0106854)*(J**3)*Z)+ APP12530
     1    ((.00110903)*(J**3)*(PDIVD**3)*Z)+((-.000313912)*(PDIVD**6)*  APP12540
     2    Z)+((.0035985)*(J**3)*AEDVAO*Z)                               APP12550
      KQ7=((-.00142121)*(PDIVD**6)*AEDVAO*Z)+((-.00383637)*J*           APP12560
     1    (AEDVAO**2)*Z)+((.0126803)*(PDIVD**2)*(AEDVAO**2)*Z)+         APP12570
     2    ((-.00318278)*(J**2)*(PDIVD**3)*(AEDVAO**2)*Z)+               APP12580
     3    ((.00334268)*(PDIVD**6)*(AEDVAO**2)*Z)                        APP12590
      KQ8=((-.00183491)*J*PDIVD*(Z**2))+((.000112451)*(J**3)*(PDIVD**2) APP12600
     1    *(Z**2))+((-.0000297228)*(J**3)*(PDIVD**6)*(Z**2))+           APP12610
     2    ((.000269551)*J*AEDVAO*(Z**2))+((.00083265)*(J**2)*AEDVAO*    APP12620
     3    (Z**2))                                                       APP12630
      KQ9=((.00155334)*(PDIVD**2)*AEDVAO*(Z**2))+((.000302683)*         APP12640
     1    (PDIVD**6)*AEDVAO*(Z**2))+((-.0001843)*(AEDVAO**2)*(Z**2))+   APP12650
     2    ((-.000425399)*(PDIVD**3)*(AEDVAO**2)*(Z**2))+                APP12660
```

```
     3    ((.C000869243)*(J**3)*(PDIVD**3)*(AEDVAC**2)*(Z**2))              APP12670
      KQ10=((-.00C4659)*(PDIVC**6)*(AEDVAC**2)*(Z**2))+                     APP12680
     1     ((.000C554194)*J*(PDIVD**6)*(AEDVAC**2)*(Z**2))                  APP12690
C                                                                           APP12700
C     NEXT,CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "REYFAC"            APP12710
C                                                                           APP12720
C     WRITE(6,*)REYNO,REYNO,REYNO                                           APP12730
      REYFAC=ALOG10(REYNO)-0.301                                            APP12740
C                                                                           APP12750
C     THEN,CALCULATE "DELKQ=DELKQ1+DELKQ2+DELKQ3"......                     APP12760
C                                                                           APP12770
      DELKQ1=(-.0C0591412)+((.00696858)*PDIVD)+                             APP12780
     1     ((-.C000666654)*Z*(PDIVD**6))+((.0160818)*(AEDVAO**2))           APP12790
      DELKQ2=((-.C009380S1)*REYFAC*PDIVD)+((-.00059593)*REYFAC*             APP12800
     1       (PDIVD**2))+((.0000782099)*(REYFAC**2)*(PDIVD**2))+            APP12810
     2     ((.0C000521S9)*REYFAC*Z*AEDVAC*(J**2))                           APP12820
      DELKQ3=((-.C000C088528)*(REYFAC**2)*Z*AEDVAC*PDIVD*J)+                APP12830
     1     ((.0C002301 71)*REYFAC*Z*(PDIVD**6))+((-.00000184341)*           APP12840
     2       (REYFAC**2)*Z*(PDIVD**6))+((-.0C400252)*REYFAC*                APP12850
     3       (AECVAO**2))+((.000220915)*(REYFAC**2)*(AEDVAO**2))            APP12860
      DELKQ=DELKQ1+DELKQ2+DELKQ3                                            APP12870
C                                                                           APP12880
C     FINALLY,CALCULATE THRUST COEFFICIENT "KC" WHERE                       APP12890
C     "KQ=KQ1+KQ2+KQ3+KQ4+KQ5+KQ6+KQ7+KQ8+KQ9+KQ1C+DELKQ"                   APP12900
C                                                                           APP12910
      KQ=KQ1+KQ2+KQ3+KQ4+KQ5+KQ6+KQ7+KQ8+KQ9+KQ10+DELKQ                     APP12920
      RETURN                                                                APP12930
      END                                                                   APP12940
```

```
      SUBROUTINE CALCKT(J,PDIVD,AEDVAO,Z,REYNO,KT)
C
C     SUBROUTINE: CALCKT                     DATE OF LAST REVISION: FEB 83
C
C     INPUT           OUTPUT                 DEFINITION
C
C     AEDVAO                                 EXPANDED AREA RATIO
C     PDIVD                                  PITCH-DIAMETER RATIO
C     Z                                      NO. OF BLADES
C     J                                      ADAVNCE RATIO
C     REYNO                                  REYNOLD'S NO. 3/4 RADIUS
C                                            (CORRECTED FOR T/C 3/4 RADIUS
C                     KT                     THRUST COEFFICIENT
C
      REAL*4 J,PDIVD,AEDVAO,Z,REYNO,KT,KT1,KT2,KT3,KT4,KT5,KT6,KT7,KT8,
     1       DELKT,DELKT1,DELKT2,DELKT3,REYFAC
C
C     FIRST, CALCULATING "KT1" THRU "KT8"......
C
      KT1=.00880496+((-.204554)*J)+((.166351)*PDIVD)+
     1               ((.158114)*(PDIVD**2))+((-.147581)*(J**2)*AEDVAO)
      KT2=((-.481497)*J*PDIVD*AEDVAO)+((.415437)*(PDIVD**2)*AEDVAO)+
     1    ((.0144043)*Z)+((-.0530054)*(J**2)*Z)+((.0143481)*PDIVD*Z)
      KT3=((.0606826)*J*PDIVD*Z)+((-.0125894)*AEDVAO*Z)+
     1    ((.0109689)*J*AEDVAO*Z)+((-.133698)*(PDIVD**3))+((.00638407)*
     2    (PDIVD**6))
      KT4=((-.00132718)*(J**2)*(PDIVD**6))+((.168496)*(J**3)*AEDVAO)+
     1    ((-.0507214)*(AEDVAO**2))+((.0854559)*(J**2)*(AEDVAO**2))+
     2    ((-.0504475)*(J**3)*(AEDVAO**2))
      KT5=((.010465)*J*(PDIVD**6)*(AEDVAO**2))+((-.00648272)*(J**2)*
     1    (PDIVD**6)*(AEDVAO**2))+((-.00841728)*(PDIVD**3)*Z)+
     2   ((.0168424)*J*(PDIVD**3)*Z)+((-.00102296)*(J**3)*(PDIVD**3)*Z)
      KT6=((-.0317791)*(PDIVD**3)*AEDVAO*Z)+((.018604)*J*(AEDVAO**2)*Z)+
     1    ((-.00410798)*(PDIVD**2)*(AEDVAO**2)*Z)+((-.000606848)*(Z**2))
     2   +((-.0049819)*J*(Z**2))
      KT7=((.0025983)*(J**2)*(Z**2))+((-.000560528)*(J**3)*(Z**2))+
     1    ((-.00163652)*J*(PDIVD**2)*(Z**2))+((-.000328787)*J*
     2    (PDIVD**6)*(Z**2))+((.000116502)*(J**2)*(PDIVD**6)*(Z**2))
      KT8=((.000690904)*AEDVAO*(Z**2))+((.00421749)*(PDIVD**3)*AEDVAO*
     1    (Z**2))+((.0000565229)*(J**3)*(PDIVD**6)*AEDVAO*(Z**2))+
     2    ((-.00146564)*(PDIVD**3)*(AEDVAO**2)*(Z**2))
C
C     NEXT,CALCULATE LOGARITHMIC REYNOLDS NUMBER FACTOR "REYFAC"
C
      WRITE(6,*)REYNO,REYNO
      REYFAC=ALOG10(REYNO)-0.301
C
C     THEN,CALCULATE "DELKT=DELKT1+DELKT2+DELKT3"......
```

```
C
      DELKT1=(.00(353485)+((-.00333758)*AEDVAC*(J**2))+
     1       ((-.C0478125)*AEDVAO*PDIVD*J)
      DELKT2=((.0C0257792)*(REYFAC**2)*AEDVAO*(J**2))+
     1       ((.0C00643192)*REYFAC*(PDIVD**6)*(J**2))+
     2       ((-.C000110636)*(REYFAC**2)*(PDIVD**6)*(J**2))
      DELKT3=((-.C000276305)*(REYFAC**2)*Z*AEDVAO*(J**2))+
     1       ((.0C00954)*REYFAC*Z*AEDVAO*PDIVD*J)+
     2       ((.0C00032049)*REYFAC*(Z**2)*AEDVAO*(PDIVD**3)*J)
      DELKT=DELKT1+DELKT2+DELKT3
C
C     FINALLY,CALCULATE THRUST COEFFICIENT "KT" WHERE
C     "KT=KT1+KT2+KT3+KT4+KT5+KT6+KT7+KT8+DELKT".....
C
      KT=KT1+KT2+KT3+KT4+KT5+KT6+KT7+KT8+DELKT
      RETURN
      END
```

```
      SUBROUTINE CALCQS(KQ,SQS)
C
C     SUBROUTINE: CALCQS                       DATE OF LAST REVISION: FEB 83
C
C     INPUT           OUTPUT                   DEFINITION
C
C     KQ                                       TORQUE COEFFICIENT
C     DIA                                      PROPELLER DIAMETER (FT)
C     N                                        PROPELLER REVOLUTION RATE(RPM
C     WATRO                                    WATER DENSITY (LBF-SEC2/FT4)
C                     SQS                      DELIVERED TORQUE (FT-LBF)
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       KQ,SQS
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE DELIVERED TORQUE REQUIRED BY PROPELLER
C
      SQS=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
      RETURN
      END
```

```
      SUBROUTINE CALCPE(KT,SPE)                                         APP13950
C                                                                       APP13960
C     SUBROUTINE: CALCPE                        DATE OF LAST REVISION: FEB 83APP13970
C                                                                       APP13980
C     INPUT             OUTPUT                  DEFINITION              APP13990
C                                                                       APP14000
C     KT                                        THRUST COEFFICIENT      APP14010
C     DIA                                       PROPELLER DIAMETER (FT) APP14020
C     N                                         PROPELLER REVOLUTION RATE(RPMAPP14030
C     WATRO                                     WATER DENSITY (LBF-SEC2/FT4) APP14040
C     TD                                        THRUST DEDUCTION        APP14050
C     WT                                        TAYLOR WAKE FRACTION    APP14060
C     V                                         VELOCITY (FT/SEC)       APP14070
C                       SPE                     EFFECTIVE POWER (HP)    APP14080
C                                                                       APP14090
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,             APP14100
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,    APP14110
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                           APP14120
     3        VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,              APP14130
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,              APP14140
     5        KT,SPE,T                                                  APP14150
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP14160
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP14170
     2AEAOCV,TCSTRS,RJ                                                  APP14180
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP14190
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP14200
C                                                                       APP14210
C     CALCULATE THRUST DEVELOPED BY PROPELLER                           APP14220
C                                                                       APP14230
      T=(KT*WATRO*(DIA**4)*((N/60.0)**2))                               APP14240
C                                                                       APP14250
C     CALCULATE EFFECTIVE HORSEPOWER DEVELOPED BY PROPELLER             APP14260
C                                                                       APP14270
      SPE=((1.0-TD)/(1.0-WT))*((T*(1.0-WT)*V)/550.0)                    APP14280
      RETURN                                                            APP14290
      END                                                               APP14300
```

```
      SUBROUTINE CAVCNA(KT,SEAOCV)
C
C     SUBROUTINE: CAVCNA                        DATE OF LAST REVISION: FEB 83
C
C     INPUT           OUTPUT                    DEFINITION
C
C     PATM                                      ATMOSPHERIC PRESSURE (PSIA)
C     WATRO                                     WATER DENSITY (LBF-SEC2/FT4)
C     PWATVA                                    VAPORIZATION PRESSURE FOR WATER
C                                               (PSIA)
C     HCL                                       DEPTH OF PROPELLER SHAFT
C                                               CENTERLINE (FT)
C     KT                                        THRUST COEFFICIENT
C     DIA                                       PROPELLER DIAMETER (FT)
C     N                                         PROPELLER REVOLUTION RATE(RPM)
C     Z                                         NO. OF BLADES
C     NOSCRW                                    NO. OF PROPELLERS
C     AEDVAO                                    PROPELLER EXPANDED AREA RATIO
C                     SEAOCV                    CONSTRAINT VARIABLE FOR PRO-
C                                               PELLER EXPANDED AREA RATIO
C                                               CONSTRAINT (SEAOCV<0)
C
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ
     3        VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5        KT,POMNPV,THRST,SEACMN,SEAOCV
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE DIFFERENCE BETWEEN STATIC PRESSURE AT SHAFT CENTERLINE
C     & WATER VAPORIZATION PRESSURE
C
      POMNPV=(PATM*144.0)+(WATRO*32.174*HCL)-(PWATVA*144.0)
C
C     DETERMINE MINIMUM REQUIRED EXPANDED AREA RATIO FOR PROPELLER(S)
C     USING "KELLER" CRITERIA FROM RELATION (13), REF 2
C
      THRST=(KT*WATRO*(DIA**4)*((N/60.0)**2))
      SEACMN=((1.3+(0.3*Z))*THRST)/((DIA**2)*POMNPV)
C
C     CORRECT ACCORDING TO NUMBER OF PROPELLERS
C
      IF(.NOT.(NOSCRW.EQ.1.0))GO TO 1
```

```
            SEAGMN=SEACMN+0.2                                         APP14810
      GO TO 3                                                         APP14820
    1 CONTINUE                                                        APP14830
      IF(.NOT.(NOSCRW.EQ.2.0))GO TO 2                                 APP14840
            SEACMN=SEACMN+0.1                                         APP14850
      GO TO 3                                                         APP14860
    2 CONTINUE                                                        APP14870
            SEACMN=SEAGMN+0.0                                         APP14880
    3 CONTINUE                                                        APP14890
      AEACMN=SEAOMN                                                   APP14900
C                                                                     APP14910
C     DETERMINE CONSTRAINT VARIABLE                                   APP14920
C                                                                     APP14930
      SEAOCV=(SEACMN/AEDVAD)-1.0                                      APP14940
      RETURN                                                          APP14950
      END                                                             APP14960
```

```
      SUBROUTINE CH75RA(C75R)                                           APP14990
C                                                                       APP15000
C                                                                       APP15010
C     SUBROUTINE:  CH75RA                   DATE OF LAST REVISION: FEB 83 APP15020
C                                                                       APP15030
C     INPUT               OUTPUT            DEFINITION                  APP15040
C                                                                       APP15050
C     AEDVAO                                EXPANED AREA RATIO          APP15060
C     DIA                                   PROPELLER DIAMETER  (FEET)  APP15070
C     Z                                     NO. OF BLADES               APP15080
C                          C75R             CHORD LENGTH AT 3/4 RADIUS  APP15090
C                                           (FEET)                      APP15100
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,              APP15110
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,     APP15120
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                            APP15130
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,               APP15140
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,               APP15150
     5       C75R                                                       APP15160
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP15170
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP15180
     2AEAOCV,TCSTRS,RJ                                                  APP15190
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP15200
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP15210
C                                                                       APP15220
C     CALCULATE CHORD LENGTH AT 3/4 RADIUS USING RELATION (17),REF 2    APP15230
C                                                                       APP15240
      C75R=(2.073*AEDVAO*DIA)/Z                                         APP15250
      RETURN                                                            APP15260
      END                                                               APP15270
```

```
      SUBROUTINE CNFGLD
C
C     SUBROUTINE: CNFGLD                      DATE OF LAST REVISION: APR 83
C
C     INPUT             OUTPUT                DEFINITION
C
C     DIA                                     PROPELLER DIAMETER (FT)
C     N                                       PROPELLER REVOLUTION RATE (RPM)
C     PDIVD                                   PITCH-DIAMETER RATIO
C     Z                                       NO. OF PROPELLER BLADES
C     PROMAT                                  PROPELLER MATERIAL IDENTIFIER
C                                                 1: CAST IRON
C                                                 2: CAST STEEL
C                                                 3: TYPE 2 BRONZE
C                                                 4: TYPE 4 NI-AL BRONZE
C                                                 5: STAINLESS STEEL
C     COMMON /AREELD/                         BLADE SECTION AREAS (FEET**2)
C     COMMON /CGX/                            LOCATION OF BLADE CROSS-SEC-
C                                             TIONAL AREA CENTROID WITH
C                                             RESPECT TO GENERATOR LINE
C                                             (FEET)
C     COMMON /CGY/                            LOCATION OF BLADE CROSS-SEC-
C                                             TIONAL AREA CENTROID WITH
C                                             RESPECT TO PITCH-REFERENCE
C                                             LINE (FEET)
C                       COMMON /CFGFD/        CENTRIFUGAL FORCE COMPONENTS,
C                                             ALONG THE PROPELLER RADIUS,
C                                             PARALLEL TO GENERATOR LINE,
C                                             WHICH ACT ON A BLADE SECTION
C                                             AT ITS NEUTRAL AXES ORIGIN
C                                             (LBF)
C                       COMMON /CMCBN/        CENTIFUGAL BENDING MOMENT COM-
C                                             PONENTS, ALONG THE PROPELLER
C                                             RADIUS, PARALLEL TO THE PITCH
C                                             REFERENCE (CHORD) LINE, WHICH
C                                             ACT ON A BLADE SECTION AT ITS
C                                             NEUTRAL AXES ORIGIN (FT-LBF)
C                       COMMON /CMCBL/        CENTIFUGAL BENDING MOMENT COM-
C                                             PONENTS, ALONG THE PROPELLER
C                                             RADIUS, NORMAL TO THE PITCH
C                                             REFERENCE (CHORD) LINE, WHICH
C                                             ACT ON A BLADE SECTION AT ITS
C                                             NEUTRAL AXES ORIGIN (FT-LBF)
C
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
     2        FCWBAL,DIACNU,AEAOCV,TCSTRS,
     3        VK,TC,WT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PATM,
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     4        FWATNA,PROMAT,DIALIM,ETARR,                                         APP15780
     5        RJ,C75R,R75R,KT,KQ                                                  APP15790
      REAL*4  AREA(10),XCG(10),YCG(10),RIXXNA(10),RIYYNA(10)                      APP15800
      REAL*4  SUMSW,SUMSVR,SUMSVT,SUMSVA                                          APP15810
      REAL*4  SMALLI(10),SMALLA(10),SMALLT(10),SMAIMA(10),                        APP15820
     1        SINBET(10),COSBET(10),                                              APP15830
     2        SUM(10),SUMR(10),SUMT(10),SUMA(10),                                 APP15840
     3        VOLO(10),XBRCGO(10),BIGTO(10),BIGAO(10),SMPO(10),SMQO(10)           APP15850
      REAL*4  CMCBN(10),CMCBL(10),BIGNO(10),RADIUS                                APP15860
      INTEGER*4 IR,IRP1,KCOUNT,I                                                  APP15870
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJLNL,APP15880
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,              APP15890
     2AEAOCV,TCSTRS,RJ                                                            APP15900
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,           APP15910
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                                        APP15920
      COMMON /AREELD/AREA                                                         APP15930
      COMMON /CGX/XCG                                                             APP15940
      COMMON /CGY/YCG                                                             APP15950
      COMMON /A2MCMX/RIYYNA                                                       APP15960
      COMMON /A2MCMY/RIXXNA                                                       APP15970
      COMMON /CFGEMN/CMCBN                                                        APP15980
      COMMON /CFGEML/CMCBL                                                        APP15990
      COMMON /CFGFD/BIGNO                                                         APP16000
      PII=3.141592654                                                             APP16010
C                                                                                 APP16020
C     CALCULATE RAKE ANGLE IN RADIANS                                             APP16030
C                                                                                 APP16040
      ETA=15.0*(PII/180.0)                                                        APP16050
C                                                                                 APP16060
C     SPECIFY WEIGHT DENSITY OF MATERIAL SELECTED WHERE...                        APP16070
C                                                                                 APP16080
C     PROMAT         MATERIAL              WEIGHT DENSITY (LBF/IN**3)             APP16090
C       1            CAST IRON              .260                                  APP16100
C       2            CAST STEEL             .284                                  APP16110
C       3            TYPE 2 BRONZE          .305                                  APP16120
C       4            TYPE 4 NI-AL BRONZE    .278                                  APP16130
C       5            STAINLESS STEEL        .283                                  APP16140
C                                                                                 APP16150
      IF(PROMAT.EQ.1.0)WD=.260                                                    APP16160
      IF(PROMAT.EQ.2.0)WD=.284                                                    APP16170
      IF(PROMAT.EQ.3.0)WD=.305                                                    APP16180
      IF(PROMAT.EQ.4.0)WD=.278                                                    APP16190
      IF(PROMAT.EQ.5.0)WD=.283                                                    APP16200
C                                                                                 APP16210
C     DETERMINE VALUES FOR...                                                     APP16220
C                                                                                 APP16230
C     SMALLI(IR)          DISTANCE TO THE PITCH REFERENCE LINE, ALONG THE         APP16240
C                         PROPELLER RADIUS, WITH RESPECT TO A LINE NORMAL         APP16250
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C                     TO THE PROPELLER SHAFT AXIS AND PASSING THROUGH   APP16260
C                     THE INTERSECTION OF THE GENERATOR LINE AND THE    APP16270
C                     PROPELLER SHAFT AXIS (FEET)                       APP16280
C     SMALLA(IR)      DISTANCE, PARALLEL TO THE PROPELLER SHAFT AXIS,   APP16290
C                     OF EACH BLADE SECTION NEUTRAL AXES ORIGIN, GIVEN  APP16300
C                     BY COORDINATES ( XCG(IR),YCG(IR) ), WITH RESPECT  APP16310
C                     TO THE INTERSECTION OF THE PITCH REFERENCE LINE   APP16320
C                     AND THE GENERATOR LINE (FEET)                     APP16330
C     SMALLT(IR)      DISTANCE, NORMAL TO THE PROPELLER SHAFT AXIS,     APP16340
C                     OF EACH BLADE SECTION NEUTRAL AXES ORIGIN, GIVEN  APP16350
C                     BY COORDINATES ( XCG(IR),YCG(IR) ), WITH RESPECT  APP16360
C                     TO THE INTERSECTION OF THE PITCH REFERENCE LINE   APP16370
C                     AND THE GENERATOR LINE (FEET)                     APP16380
C                                                                       APP16390
C     ... FOR EACH BLADE SECTION ALONG THE PROPELLER RADIUS             APP16400
C                                                                       APP16410
      DO 9 IR=2,10                                                      APP16420
         IF(.NOT.(Z.EQ.4.0))GO TO 7                                     APP16430
            IF(.NOT.(IR.EQ.2))GO TO 2                                   APP16440
               RF=0.822                                                 APP16450
            GO TO 6                                                     APP16460
2           CONTINUE                                                    APP16470
            IF(.NOT.(IR.EQ.3))GO TO 3                                   APP16480
               RF=0.887                                                 APP16490
            GO TO 6                                                     APP16500
3           CONTINUE                                                    APP16510
            IF(.NOT.(IR.EQ.4))GO TO 4                                   APP16520
               RF=0.950                                                 APP16530
            GO TO 6                                                     APP16540
4           CONTINUE                                                    APP16550
            IF(.NOT.(IR.EQ.5))GO TO 5                                   APP16560
               RF=0.992                                                 APP16570
            GO TO 6                                                     APP16580
5           CONTINUE                                                    APP16590
               RF=1.00                                                  APP16600
6           CONTINUE                                                    APP16610
            DENOM=SQRT(((RF*PDIVD)**2)+(PII**2))                        APP16620
            SINBET(IR)=(RF*PDIVD)/DENOM                                 APP16630
            COSBET(IR)=(PII)/DENOM                                      APP16640
         GO TO 8                                                        APP16650
7        CONTINUE                                                       APP16660
            DENOM=SQRT((PDIVD**2)+(PII**2))                             APP16670
            SINBET(IR)=(PDIVD)/DENOM                                    APP16680
            COSBET(IR)=(PII)/DENOM                                      APP16690
8        CONTINUE                                                       APP16700
         SMALLI(IR)=(DIA/2.0)*(FLOAT(IR)/10.0)*(TAN(ETA))               APP16710
         SMALLA(IR)=(XCG(IR)*SINBET(IR))+(YCG(IR)*COSBET(IR))           APP16720
         SMALLT(IR)=(XCG(IR)*COSBET(IR))-(YCG(IR)*SINBET(IR))           APP16730
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```
          SMAIMA(IR)=SMALLI(IR)-SMALLA(IR)
    9 CONTINUE
C
C     CALCULATE TABULAR SUMMATIONS FOR INTEGRATION ALONG THE PROPELLER
C     RADIUS
C
      DO 10 IR=2,9
          IRP1=IR+1
          SUM(IR)=AREA(IR)+AREA(IRP1)
          SUMR(IR)=(FLOAT(IR)*AREA(IR))+(FLOAT(IRP1)*AREA(IRP1))
          SUMT(IR)=(SMALLT(IR)*AREA(IR))+(SMALLT(IRP1)*AREA(IRP1))
          SUMA(IR)=(SMAIMA(IR)*AREA(IR))+(SMAIMA(IRP1)*AREA(IRP1))
   10 CONTINUE
C
C     INTEGRATE ALONG THE PROPELLER RADIUS TO DETERMINE THE FORCE AND
C     BENDING MOMENT COMPONENTS,ACTING ON A BLADE SECTION AT ITS NEUTRAL
C     AXES ORIGIN, WHICH ARE IMPOSED BY CENTRIFUGAL LOADING OF THE BLADE
C     ELEMENT VOLUME ABOVE THE BLADE SECTION UNDER CONSIDERATION
C
      DO 12 IR=2,9
          KOUNT=IR
          SUMSV=0.0
          SUMSVR=0.0
          SUMSVT=0.0
          SUMSVA=0.0
          DO 11 I=KOUNT,9
              SUMSV=SUMSV+SUM(I)
              SUMSVR=SUMSVR+SUMR(I)
              SUMSVT=SUMSVT+SUMT(I)
              SUMSVA=SUMSVA+SUMA(I)
   11     CONTINUE
CC
CC        DETERMINE BLADE ELEMENT VOLUME (FT**3) ABOVE THE BLADE
CC        SECTION UNDER CONSIDERATION
CC
          VOLO(IR)=0.5*(DIA/2.0)*(0.1)*(SUMSV)
CC
CC        DETERMINE RADIAL FRACTION OF THE BLADE ELEMENT VOLUME'S CG
CC        WITH RESPECT TO THE PROPELLER SHAFT AXIS
CC
          XBRCGO(IR)=(SUMSVR/SUMSV)/10.0
CC
CC        DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, NORMAL TO
CC        THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG
CC        WITH RESPECT TO THE PROPELLER SHAFT AXIS
CC
          BIGTO(IR)=(SUMSVT/SUMSV)
CC
```

```
CC          DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, PARALLEL  APP17220
CC          TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CGAPP17230
CC          WITH RESPECT TO THE PROPELLER SHAFT AXIS                     APP17240
CC                                                                       APP17250
            BIGAO(IR)=(SUMSVA/SUMSV)                                     APP17260
CC                                                                       APP17270
CC          DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, NORMAL TO APP17280
CC          THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CG   APP17290
CC          WITH RESPECT TO THE BLADE SECTION UNDER CONSIDERATION        APP17300
CC                                                                       APP17310
            SMPO(IR)=((FLOAT(IR)/10.0)/XBRCGO(IR))*BIGTO(IR)             APP17320
CC                                                                       APP17330
CC          DETERMINE DISTANCE (FEET) FROM THE GENERATOR LINE, PARALLEL  APP17340
CC          TO THE PROPELLER SHAFT AXIS, OF THE BLADE ELEMENT VOLUME'S CGAPP17350
CC          WITH RESPECT TO THE BLADE SECTION UNDER CONSIDERATION        APP17360
CC                                                                       APP17370
            SMQO(IR)=BIGAO(IR)-(((DIA/2.0)*(FLOAT(IR)/10.0))*TAN(ETA))   APP17380
CC                                                                       APP17390
CC          CALCULATE FORCE AND BENDING MOMENT COMPONENTS WHERE...       APP17400
CC                                                                       APP17410
CC          BIGNO(IR)          CENTRIFUGAL FORCE ACTING AT BLADE SECTION APP17420
CC                             NEUTRAL AXES ORIGIN                       APP17430
CC          CMCBN(IR)          BENDING MOMENT COMPONENT, IMPOSED BY CENTRI-APP17440
CC                             FUGAL LOADING, PARALLEL TO PITCH REFERENCE APP17450
CC                             (CHORD) LINE OF A BLADE SECTION           APP17460
CC          CMCBL(IR)          BENDING MOMENT COMPONENT, IMPOSED BY CENTRI-APP17470
CC                             FUGAL LOADING, NORMAL TO PITCH REFERENCE  APP17480
CC                             (CHORD) LINE OF A BLADE SECTION           APP17490
CC                                                                       APP17500
            RADIUS=(FLOAT(IR)/10.0)*(DIA/2.0)                            APP17510
            BIGNO(IR)=((WD*1728.0*VOLO(IR)*((2.0*PII*(N/60.0))**2)*      APP17520
         1           (DIA/2.0)*XBRCGO(IR))/32.174)*                      APP17530
         2           (RADIUS/(SQRT((RADIUS**2)+((SMPO(IR))**2))))        APP17540
            CMCBN(IR)=BIGNO(IR)*((SMPO(IR)*SINBET(IR))+                  APP17550
         1                     (SMQO(IR)*COSBET(IR))+YCG(IR))            APP17560
            CMCBL(IR)=BIGNO(IR)*(XCG(IR)+                                APP17570
         1           ((SMQO(IR)*SINBET(IR))-(SMPO(IR)*COSBET(IR))))      APP17580
      12 CONTINUE                                                        APP17590
         RETURN                                                          APP17600
         END                                                             APP17610
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```
      SUBROUTINE COEFSA(SJ,R75R,KT,KQ)
C
C     SUBROUTINE: COEFSA                       DATE OF LAST REVISION: FEB 83
C
C     INPUT             OUTPUT                 DEFINITION
C
C     AEDVAO                                   EXPANDED AREA RATIO
C     PDIVD                                    PITCH-DIAMETER RATIO
C     Z                                        NO. OF BLADES
C     SJ                                       ADAVNCE COEFFICIENT
C     R75R                                     REYNOLD'S NO. 3/4 RADIUS
C                                              (CORRECTED FOR T/C 3/4 RADIUS
C                       KT                     THRUST COEFFICIENT
C                       KQ                     TORQUE COEFFICIENT
C
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3        VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5        R75R,KT,KQ,SJ
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE THRUST & TORQUE COEFFICIENTS USING THE WAGENINGEN SERIES
C     POLYNOMIALS GIVEN IN TABLES (5) AND (6), REF 2
C
      CALL CALCKT(SJ,PDIVD,AEDVAO,Z,R75R,KT)
      CALL CALCKQ(SJ,PDIVD,AEDVAO,Z,R75R,KQ)
      RETURN
      END
```

```
      SUBROUTINE DICNUA(SIACNU)
C
C     SUBROUTINE: DICNUA                            DATE OF LAST REVISION: FEB 83
C
C     INPUT             OUTPUT                      DEFINITION
C
C     DIA                                           PROPELLER DIAMETER (FT)
C     DIALIM                                        MAXIMUM DIAMETER PERMITTED BY
C                                                   HULL'S AFTERBODY (FT)
C                       SIACNU                      CONSTRAINT VARIABLE (UPPER
C                                                   BOUND) ON DIAMETER (DIACNU<0)
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       SIACNU
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     DETERMINE CONSTRAINT VARIABLE OF PROPELLER DIAMETER'S UPPER BOUND
C     CONSTRAINT
C
      SIACNU=(DIA/DIALIM)-1.0
      RETURN
      END
```

```
      SUBROUTINE EXTCCN(Z,AECVAO,TC75R,AEAOCL,AEAOCU,TC75CL,TC75CU)
C
C     SUBROUTINE: EXTCCN                   DATE OF LAST REVISION: FEB 83
C
C     INPUT             OUTPUT             DEFINITION
C
C     Z                                    NO. OF BLADES
C     AECVAO                               EXPANDED AREA RATIO
C     TC75R                                BLADE THICKNESS-TO-CHORD RATIO
C                       AEAOCL             EXPANDED AREA RATIO CONSTRAINT
C                                          VARIABLE (LOWER BOUND)(AEAOCL<0)
C                       AEAOCU             EXPANDED AREA RATIO CONSTRAINT
C                                          VARIABLE (UPPER BOUND)(AEAOCU<0)
C                       TC75CL             BLADE THICKNESS-TO-CHORD RATIO
C                                          CONSTRAINT VARIABLE (LOWER BOUND)
C                                          (TC75CL<0)
C                       TC75CU             BLADE THICKNESS-TO-CHORD RATIO
C                                          CONSTRAINT VARIABLE (UPPER BOUND)
C                                          (TC75CL<0)
C
      REAL*4 Z,AECVAO,TC75R,AEAOCL,AEAOCU,TC75CL,TC75CU,
     1       AEAOLO,AEAOUP,TC75LO,TC75UP
C
C     SET LIMITS ON EXPANDED AREA RATIO BASED ON NUMBER OF BLADES
C
      IF(.NOT.(Z.EQ.3.0))GO TO 1
           AEACLO=0.35
           AEACUP=0.80
      GO TO 6
    1 CONTINUE
      IF(.NOT.(Z.EQ.4.0))GO TO 2
           AEACLO=0.40
           AEACUP=1.00
      GO TO 6
    2 CONTINUE
      IF(.NOT.(Z.EQ.5.0))GO TO 3
           AEACLO=0.45
           AEACUP=1.05
      GO TO 6
    3 CONTINUE
      IF(.NOT.(Z.EQ.6.0))GO TO 4
           AEACLO=0.50
           AEACUP=0.80
      GO TO 6
    4 CONTINUE
      IF(.NOT.(Z.EQ.7.0))GO TO 5
           AEACLO=0.55
           AEACUP=0.85
```

```
      GO TO 6
    5 CONTINUE
         AEACLO=0.35
         AEACUP=1.05
    6 CONTINUE
C
C     DETERMINE CONSTRAINT VARIABLES FOR EXPANDED AREA RATIO CONSTRAINT
C
      AEACCL=AEAOLO-AEDVAO
      AEACCU=AEDVAO-AEAOUP
C
C     DETERMINE CONSTRAINT VARIABLES FOR BLADE THICKNESS-TO-CHORD RATIO
C     CONSTRAINT
C
      TC75LO=(0.5)*(((0.0185-0.00125*Z)*Z)/(2.073*AEAOUP))
      TC75UP=(4.0)*(((0.0185-0.00125*Z)*Z)/(2.073*AEAOLO))
      TC75CL=TC75LO-TC75R
      TC75CU=TC75R-TC75UP
      RETURN
      END
```

```
      SUBROUTINE HYDLD(KQ,KT)
C
C     SUBROUTINE: HYDLD                    DATE OF LAST REVISION: APR 83
C
C     INPUT           OUTPUT               DEFINITION
C
C     DIA                                  PROPELLER DIAMETER (FT)
C     N                                    PROPELLER REVOLUTION RATE (RPM)
C     PDIVD                                PITCH-DIAMETER RATIO
C     KQ                                   TORQUE COEFFICIENT
C     KT                                   THRUST COEFFICIENT
C     WATRO                                WATER DENSITY (LBF-SEC2/FT4)
C     Z                                    NO. OF PROPELLER BLADES
C                     COMMON/HYDMOMN/      HYDRODYNAMIC MOMENTS PARALLEL
C                                          TO BLADE SECTION PITCH REFER-
C                                          ENCE (CHORD) LINE (FT-LBF)
C                     COMMON/HYDMOML/      HYDRODYNAMIC MOMENTS NORMAL
C                                          TO BLADE SECTION PITCH REFER-
C                                          ENCE (CHORD) LINE (FT-LBF)
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PRCMAT,DIALIM,ETARR,
     5       RJ,C75R,R75R,KT,KQ
      REAL*4 HMPN(10),HMPL(10),XO,PHI1(10),PHI2(10),GAM2(10),T,Q,
     1       EMT(10),BMQ(10),DENOM,RF,PII
      INTEGER*4 IR
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PRCMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
      COMMON /HYMOMN/HMPN
      COMMON /HYMOML/HMPL
      PII=3.141592654
C
C     DETERMINE VALUES ALONG THE PROPELLER RADIUS OF VARIOUS FUNCTIONS
C     OF XO AND XF DEFINED BY BRACKETED EXPRESSIONS IN RELATIONS (4),
C     (9) AND (19), REF 8
C
      DO 1 IR=2,10
         XO=(FLOAT(IR))/10.0
         PHI1(IR)=(1.0/15.0)*
     1            (8.0+(4.0*XO)+(3.0*(XO**2))-(15.0*(XO**3)))*
     2            (SQRT(1.0-XO))
         PHI2(IR)=(2.0/45.0)*
```

```
      1          (8.0-(8.0*X0)-(3.0*(X0**2))-(2.0*(X0**3))+
      2           (5.0*(X0**4)))*
      3          (SQRT(1.C-X0))
         GAM2(IF)=(2.0/15.0)*
      1          (4.0-(5.0*X0)-(2.0*(X0**2))+(3.0*(X0**3)))*
      2          (SQRT(1.C-X0))
    1 CONTINUE
C
C     CALCULATE THRUST DEVELOPED BY PROPELLER
C
      T=(KT*WATRO*(DIA**4)*((N/60.0)**2))
C
C     CALCULATE TCRQUE REQUIRED BY PRCPELLER
C
      Q=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
C
C     CALCULATE BENDING MOMENTS DUE TO THRUST ( BMT(IR) ) AND TORQUE
C     ( BMQ(IF) ) ALONG THE PROPELLER RADIUS USING RELATIONS (10) AND
C     (26) RESPECTIVELY, REF 8
C
      DO 2 IR=2,1C
         BMT(IR)=((T*(DIA/2.0))/Z)*(PHI2(IR)/PHI1(2))
         BMQ(IR)=(Q/Z)*(GAM2(IR)/PHI1(2))
    2 CONTINUE
C
C     RESCLVE CALCULATED BENDING MOMENTS INTO COMPONENTS NORMAL AND
C     PARALLEL TO PITCH REFERENCE (CHORD) LINE FOR EACH BLADE SECTION
C     ALONG THE PROPELLER RADIUS USING RELATICNS (42) AND (43), REF 8 .
C     REMEMBER TO ACCCUNT FCR PITCH REDUCTION OF FOUR BLADE (Z=4.0)
C     PROPELLERS
C
      DO 10 IR=2,10
         IF(.NOT.(Z.EQ.4.0))GO TO 8
            IF(.NCT.(IR.EQ.2))GO TO 3
               RF=0.822
            GC TO 7
    3       CCNTINUE
            IF(.NCT.(IR.EQ.3))GO TO 4
               RF=0.887
            GC TO 7
    4       CCNTINUE
            IF(.NCT.(IR.EQ.4))GO TO 5
               RF=0.950
            GC TC 7
    5       CCNTINUE
            IF(.NCT.(IR.EQ.5))GO TO 6
               RF=C.992
            GC TO 7
```

```
 6          CONTINUE                                                      APP19970
                 RF=1.00                                                  APP19980
 7          CONTINUE                                                      APP19990
            DENOM=SQRT(((RF*PDIVD)**2)+(PII**2))                          APP20000
            HMPN(IR)=(BMT(IR)*(PII/DENOM))+                               APP20010
     1               (BMQ(IR)*((RF*PDIVD)/DENOM))                         APP20020
            HMPL(IR)=(BMT(IR)*((RF*PDIVD)/DENOM))-                        APP20030
     1               (BMQ(IR)*(PII/DENOM))                                APP20040
         GO TO 9                                                          APP20050
 8       CONTINUE                                                         APP20060
            DENOM=SQRT((PDIVD**2)+(PII**2))                               APP20070
            HMPN(IR)=(BMT(IR)*(PII/DENOM))+                               APP20080
     1               (BMQ(IR)*(PDIVD/DENOM))                              APP20090
            HMPL(IR)=(BMT(IR)*(PDIVD/DENOM))-                             APP20100
     1               (BMQ(IR)*(PII/DENOM))                                APP20110
 9       CONTINUE                                                         APP20120
10 CONTINUE                                                               APP20130
   RETURN                                                                 APP20140
   END                                                                    APP20150
```

```
      SUBROUTINE JCNA(RJ,RJCNL,RJCNU)                                   APP2C180
C                                                                       APP2C190
C     SUBROUTINE: JCNA                         DATE OF LAST REVISION: FEB 83APP2C200
C                                                                       APP2C210
C     INPUT             OUTPUT                 DEFINITION               APP2C220
C                                                                       APP20230
C     RJ                                       ADVANCE COEFFICIENT      APP2C240
C                       RJCNL                  CONSTRAINT VARIABLE FOR AD-  APP20250
C                                              VANCE COEFFICIENT(LOWER BOUNDAPP2C260
C                                              (RJCNL<0)                APP2C270
C                       RJCNU                  CONSTRAINT VARIABLE FOR AD-  APP2C280
C                                              VANCE COEFFICIENT(UPPER BOUNDAPP2C290
C                                              (RJCNU)                  APP2C300
      REAL*4 RJ,RJCON,RJCNL,RJCNU                                       APP2C310
C                                                                       APP2C320
C     DETERMINE CONSTRAINT VARIABLE FOR ADVANCE COEFFICIENT CONSTRAINT  APP2C330
C                                                                       APP2C340
      RJCON=RJ/1.6                                                      APP2C350
      RJCNL=0.0-RJCON                                                   APP2C360
      RJCNU=RJCON-1.0                                                   APP2C370
      RETURN                                                            APP2C380
      END                                                               APP2C390
```

```
      SUBROUTINE OPWEFF(RJ,KT,KQ,ETAO)
C
C     SUBROUTINE: OPWEFF                         DATE OF LAST REVISION: FEB 83
C
C     INPUT              OUTPUT                  DEFINITION
C
C     RJ                                         ADVANCE RATIO
C     KT                                         THRUST COEFFICIENT
C     KQ                                         TORQUE COEFFICIENT
C                        ETAO                    OPEN WATER EFFICIENCY
C
      REAL*4 RJ,KT,KQ,ETAO,PII
      PII=3.141592654
C
C     CALCULATE OPEN WATER EFFICIENCY
C
      IF(KT.LE.0.0)KT=0.0
      IF(KQ.LE.0.0)KQ=0.0001
      ETAO=(RJ*KT)/(2.0*PII*KQ)
      RETURN
      END
```

```
      SUBROUTINE RDCAL(RDIA)                                            APP20650
C                                                                       APP20660
C                                                                       APP20670
C     SUBROUTINE:  RDCAL                    DATE OF LAST REVISION: FEB 83 APP20680
C                                                                       APP20690
C     INPUT               OUTPUT            DEFINITION                  APP20700
C                                                                       APP20710
C     V                                     VELOCITY  (FT/SEC)          APP20720
C     N                                     PROPELLER REVOLUTION RATE(RPM)APP20730
C     RJ                                    ADVANCE RATIO               APP20740
C     WT                                    WAKE FRACTION               APP20750
C                         RDIA              PROPELLER DIAMETER (FEET)   APP20760
C                                                                       APP20770
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,              APP20780
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,     APP20790
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                            APP20800
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,               APP20810
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,               APP20820
     5       RDIA                                                       APP20830
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP20840
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP20850
     2AEAOCV,TCSTRS,RJ                                                  APP20860
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP20870
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP20880
C                                                                       APP20890
C     CALCULATE PROPELLER DIAMETER                                      APP20900
C                                                                       APP20910
      RDIA=(V*(1.0-WT))/((N/60.0)*RJ)                                   APP20920
      RETURN                                                            APP20930
      END                                                               APP20940
```

```
      SUBROUTINE REYCNA(R75R,R75RCL,R75RCU)                             APP20970
C                                                                       APP20980
C     SUBROUTINE: REYCNA                     DATE OF LAST REVISION: FEB 83APP20990
C                                                                       APP21000
C     INPUT           OUTPUT                 DEFINITION                 APP21010
C                                                                       APP21020
C     R75R                                   REYNOLDS NO. 3/4 RADIUS    APP21030
C                                            (CORRECTED FOR T/C 3/4 RADIUSAPP21040
C                     R75RCL                 CONSTRAINT VARIABLE FOR REY- APP21050
C                                            NOLDS NO.(CORRECTED)       APP21060
C                                            (LOWER BOUND) (R75RCL<0)   APP21070
C                     R75RCU                 CONSTRAINT VARIABLE FOR REY- APP21080
C                                            NOLDS NO. (CORRECTED)      APP21090
C                                            (UPPER BOUND) (R75RCU<0)   APP21100
C                                                                       APP21110
      REAL*4 R75R,R75RCN,R75RCL,R75RCU                                  APP21120
C                                                                       APP21130
C     DETERMINE CONSTRAINT VARIABLE FOR CORRECTED REYNOLDS NO. CONSTRAINAPP21140
C                                                                       APP21150
      R75RCN=R75R/2000000.0                                             APP21160
      R75RCL=1.0-R75RCN                                                 APP21170
      R75RCU=R75RCN-1000.0                                              APP21180
      RETURN                                                            APP21190
      END                                                               APP21200
```

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      SUBROUTINE REY75R(C75R,R75R)                                      APP21230
C                                                                       APP21240
C     SUBROUTINE:  REY75R                     DATE OF LAST REVISION: FEB 83APP21250
C                                                                       APP21260
C     INPUT             OUTPUT                DEFINITION                APP21270
C                                                                       APP21280
C     C75R                                    CHORD LENGTH AR 3/4 RADIUS   APP21290
C                                                            (FEET)    APP21300
C     N                                       PROPELLER REVOLUTIONS (RPM)  APP21310
C     DIA                                     PROPELLER DIAMETER (FEET)    APP21320
C     Z                                       NO. OF BLADES             APP21330
C     TC75R                                   BLADE SECTION THICKNESS-TO-  APP21340
C                                             CHORD RATIO AT 3/4 RADIUS    APP21350
C     AEDVAO                                  EXPANDED AREA RATIO       APP21360
C     WATNU                                   KINEMATIC VISCOSITY       APP21370
C                       R75R                  REYNOLDS NO. AT 3/4 RADIUS   APP21380
C                                             CORRECTED FOR CORRECTED FOR  APP21390
C                                             BLADE THICKNESS EFFECTS   APP21400
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,              APP21410
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,     APP21420
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                            APP21430
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,               APP21440
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,               APP21450
     5       C75R,PII,VA,R75RUN,TC75WS,NUM,DENOM,R75R                   APP21460
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP21470
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP21480
     2AEAOCV,TCSTRS,RJ                                                  APP21490
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP21500
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP21510
      PII=3.141592654                                                   APP21520
C                                                                       APP21530
C     CALCULATE SPEED OF ADVANCE                                        APP21540
C                                                                       APP21550
      VA=V*(1.0-WT)                                                     APP21560
C                                                                       APP21570
C     CALCULATE UNCORRECTED REYNOLDS NUMBER AT 3/4 PROPELLER RADIUS     APP21580
C     USING RELATION (10), REF 2                                        APP21590
C                                                                       APP21600
      R75RUN=(1.0/WATNU)*C75R*SQRT((VA**2)+((.75*PII*(N/60.0)*DIA)**2)) APP21610
C                                                                       APP21620
C     DETERMINE BLADE THICKNESS-TO-CHORD RATIO BASED ON A SPECIFIC "Z" &APP21630
C     "AEDVAO" USING RELATION (11), REF 2                               APP21640
C                                                                       APP21650
      TC75WS=((0.0185-(0.00125*Z))*Z)/(2.073*AEDVAO)                    APP21660
C                                                                       APP21670
C     DETERMINE REYNOLDS NUMBER AT 3/4 RADIUS, CORECTED FOR BLADE       APP21680
C     THICKNESS-TO-CHORD RATIO "TC75R", USING RELATION (12), REF 2      APP21690
C                                                                       APP21700
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```
      NUM=1.0+(2.0*TC75WS)                                              APP21710
      DENOM=1.0+(2.0*TC75R)                                             APP21720
      R75R=EXP(4.6052+((SQRT(NUM/DENOM))*(ALOG(R75RUN)-4.6052)))        APP21730
      RETURN                                                            APP21740
      END                                                               APP21750
```

```
      SUBROUTINE RJCAL(J)
C
C
C     SUBROUTINE:  RJCAL                       DATE OF LAST REVISION: FEB 83
C
C     INPUT               OUTPUT               DEFINITION
C
C     V                                        VELOCITY  (FT/SEC)
C     DIA                                      PROPELLER DIAMETER  (FEET)
C     N                                        PROPELLER REVOLUTION RATE(RPM)
C     WT                                       WAKE FRACTION
C                         J                    ADVANCE RATIO
C
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       J
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     CALCULATE ADVANCE RATIO
C
      J=(V*(1.0-WT))/(DIA*(N/60.0))
      RETURN
      END
```

```
      SUBROUTINE RNCAL(RN)                                              APP22100
C                                                                       APP22110
C                                                                       APP22120
C     SUBROUTINE:  RNCAL                      DATE OF LAST REVISION: FEB 83 APP22130
C                                                                       APP22140
C     INPUT               OUTPUT              DEFINITION                APP22150
C                                                                       APP22160
C     V                                       VELOCITY  (FT/SEC)        APP22170
C     DIA                                     PROPELLER DIAMETER  (FEET)    APP22180
C     RJ                                      ADVANCE RATIO             APP22190
C     WT                                      WAKE FRACTION             APP22200
C                         RN                  PROPELLER REVOLUTION RATE(RPM)APP22210
C                                                                       APP22220
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,             APP22230
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,    APP22240
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                           APP22250
     3        VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,              APP22260
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,              APP22270
     5        RN                                                        APP22280
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP22290
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP22300
     2AEAOCV,TCSTRS,RJ                                                  APP22310
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP22320
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP22330
C                                                                       APP22340
C     CALCULATE PROPELLER REVOLUTION RATE                               APP22350
C                                                                       APP22360
      RN=60.0*((V*(1.0-WT))/(DIA*RJ))                                   APP22370
      RETURN                                                            APP22380
      END                                                               APP22390
```

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      SUBROUTINE SIGNDS                                                 APP22420
C                                                                       APP22430
C     SUBROUTINE: SIGNDS                  DATE OF LAST REVISION: APR 83 APP22440
C                                                                       APP22450
C     INPUT             OUTPUT            DEFINITION                    APP22460
C                                                                       APP22470
C     COMMON /AREFLD/                     BLADE SECTION AREAS (FEET**2) APP22480
C     COMMON /VALL1/                      ORDINATE OF CRITICAL POINT NO.APP22490
C                                         1 ON BLADE SECTION PERIPHERY  APP22500
C                                         WITH RESPECT TO A SYSTEM OF   APP22510
C                                         AXES PARALLEL AND NORMAL TO   APP22520
C                                         PITCH-REFERENCE LINE WITH ORI-APP22530
C                                         GIN AT THE CENTROID OF THE    APP22540
C                                         SECTION (FEET)                APP22550
C     COMMON /VALW1/                      ABCISSA OF CRITICAL POINT NO. APP22560
C                                         1 ON BLADE SECTION PERIPHERY  APP22570
C                                          WITH RESPECT TO A SYSTEM OF  APP22580
C                                         AXES PARALLEL AND NORMAL TO   APP22590
C                                         PITCH-REFERENCE LINE WITH ORI-APP22600
C                                         GIN AT THE CENTROID OF THE    APP22610
C                                         SECTION (FEET)                APP22620
C     COMMON /VALL2/                      ORDINATE OF CRITICAL POINT NO.APP22630
C                                         2 ON BLADE SECTION PERIPHERY  APP22640
C                                         WITH RESPECT TO A SYSTEM OF   APP22650
C                                         AXES PARALLEL AND NORMAL TO   APP22660
C                                         PITCH-REFERENCE LINE WITH ORI-APP22670
C                                         GIN AT THE CENTROID OF THE    APP22680
C                                         SECTION (FEET)                APP22690
C     COMMON /VALW2/                      ABCISSA OF CRITICAL POINT NO. APP22700
C                                         2 ON BLADE SECTION PERIPHERY  APP22710
C                                         WITH RESPECT TO A SYSTEM OF   APP22720
C                                         AXES PARALLEL AND NORMAL TO   APP22730
C                                         PITCH-REFERENCE LINE WITH ORI-APP22740
C                                         GIN AT THE CENTROID OF THE    APP22750
C                                         SECTION (FEET)                APP22760
C     COMMON /VALL3/                      ORDINATE OF CRITICAL POINT NO.APP22770
C                                         3 ON BLADE SECTION PERIPHERY  APP22780
C                                         WITH RESPECT TO A SYSTEM OF   APP22790
C                                         AXES PARALLEL AND NORMAL TO   APP22800
C                                         PITCH-REFERENCE LINE WITH ORI-APP22810
C                                         GIN AT THE CENTROID OF THE    APP22820
C                                         SECTION (FEET)                APP22830
C     COMMON /VALW3/                      ABCISSA OF CRITICAL POINT NO. APP22840
C                                         3 ON BLADE SECTION PERIPHERY  APP22850
C                                         WITH RESPECT TO A SYSTEM OF   APP22860
C                                         AXES PARALLEL AND NORMAL TO   APP22870
C                                         PITCH-REFERENCE LINE WITH ORI-APP22880
C                                         GIN AT THE CENTROID OF THE    APP22890
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C                                                   SECTION (FEET)                    APP22900
C         COMMON /VALL4/                            ORDINATE OF CRITICAL POINT NO.APP22910
C                                                   4 ON BLADE SECTION PERIPHERY      APP22920
C                                                   WITH RESPECT TO A SYSTEM OF       APP22930
C                                                   AXES PARALLEL AND NORMAL TO       APP22940
C                                                   PITCH-REFERENCE LINE WITH ORI-APP22950
C                                                   GIN AT THE CENTROID OF THE        APP22960
C                                                   SECTION (FEET)                    APP22970
C         COMMON /VALW4/                            ABCISSA OF CRITICAL POINT NO.     APP22980
C                                                   4 ON BLADE SECTION PERIPHERY      APP22990
C                                                   WITH RESPECT TO A SYSTEM OF       APP23000
C                                                   AXES PARALLEL AND NORMAL TO       APP23010
C                                                   PITCH-REFERENCE LINE WITH ORI-APP23020
C                                                   GIN AT THE CENTROID OF THE        APP23030
C                                                   SECTION (FEET)                    APP23040
C         COMMON /A2MCMX/                           MOMENT OF INERTIA ABOUT NEU-      APP23050
C                                                   TRAL AXIS PARALLEL TO GENERA-     APP23060
C                                                   TOR LINE, PASSING THROUGH         APP23070
C                                                   BLADE CROSS SECTION CENTROID      APP23080
C                                                   (FEET**4)                         APP23090
C         COMMON /A2MCMY/                           MOMENT OF INERTIA ABOUT NEU-      APP23100
C                                                   TRAL AXIS PARALLEL TO PITCH       APP23110
C                                                   REFERENCE LINE,PASSING THROUGHAPP23120
C                                                   BLADE CROSS SECTION CENTROID      APP23130
C         COMMON /HYDMOMN/                          HYDRODYNAMIC MOMENTS PARALLEL     APP23140
C                                                   TO BLADE SECTION PITCH REFER-     APP23150
C                                                   ENCE (CHORD) LINE (FT-LBF)        APP23160
C         COMMON /HYDMOML/                          HYDRODYNAMIC MOMENTS NORMAL       APP23170
C                                                   TO BLADE SECTION PITCH REFER-     APP23180
C                                                   ENCE (CHORD) LINE (FT-LBF)        APP23190
C         COMMON /CFGFD/                            CENTRIFUGAL FORCE COMPONENTS,     APP23200
C                                                   ALONG THE PROPELLER RADIUS,       APP23210
C                                                   PARALLEL TO GENERATOR LINE,       APP23220
C                                                   WHICH ACT ON A BLADE SECTION      APP23230
C                                                   AT ITS NEUTRAL AXES ORIGIN        APP23240
C                                                   (LBF)                             APP23250
C         COMMON /CMCEN/                            CENTIFUGAL BENDING MOMENT COM-APP23260
C                                                   PONENTS, ALONG THE PROPELLER      APP23270
C                                                   RADIUS, PARALLEL TO THE PITCH     APP23280
C                                                   REFERENCE (CHORD) LINE, WHICH     APP23290
C                                                   ACT ON A BLADE SECTION AT ITS     APP23300
C                                                   NEUTRAL AXES ORIGIN (FT-LBF)      APP23310
C         COMMON /CMCEL/                            CENTIFUGAL BENDING MOMENT COM-APP23320
C                                                   PONENTS, ALONG THE PROPELLER      APP23330
C                                                   RADIUS, NORMAL TO THE PITCH       APP23340
C                                                   REFERENCE (CHORD) LINE, WHICH     APP23350
C                                                   ACT ON A BLADE SECTION AT ITS     APP23360
C                                                   NEUTRAL AXES ORIGIN (FT-LBF)      APP23370
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C                    COMMON /STRES1/   DIRECT STRESS AT CRITICAL        APP23380
C                                      POINT 1 AT BLADE SECTIONS        APP23390
C                                      ALONG THE PROPELLER RADIUS       APP23400
C                                      (LBF/FT**2)                      APP23410
C                    COMMON /STRES2/   DIRECT STRESS AT CRITICAL        APP23420
C                                      POINT 2 AT BLADE SECTIONS        APP23430
C                                      ALONG THE PROPELLER RADIUS       APP23440
C                                      (LBF/FT**2)                      APP23450
C                    COMMON /STRES3/   DIRECT STRESS AT CRITICAL        APP23460
C                                      POINT 3 AT BLADE SECTIONS        APP23470
C                                      ALONG THE PROPELLER RADIUS       APP23480
C                                      (LBF/FT**2)                      APP23490
C                    COMMON /STRES4/   DIRECT STRESS AT CRITICAL        APP23500
C                                      POINT 4 AT BLADE SECTIONS        APP23510
C                                      ALONG THE PROPELLER RADIUS       APP23520
C                                      (LBF/FT**2)                      APP23530
      REAL*4  AREA(10),RIXXNA(10),RIYYNA(10),                           APP23540
     1        U1(10),U2(10),U3(10),U4(10),W1(10),W2(10),W3(10),W4(10),  APP23550
     2        HMPN(10),HMPL(10),CMCBN(10),CMCBL(10),BIGNO(10)           APP23560
      REAL*4  SIGCF(10),TOTBMN(10),TOTBML(10),                          APP23570
     1        SIG1(10),SIG2(10),SIG3(10),SIG4(10)                       APP23580
      INTEGER*4 IR                                                      APP23590
      COMMON /AREELD/AREA                                               APP23600
      COMMON /VALL1/U1                                                  APP23610
      COMMON /VALL2/U2                                                  APP23620
      COMMON /VALL3/U3                                                  APP23630
      COMMON /VALL4/U4                                                  APP23640
      COMMON /VALW1/W1                                                  APP23650
      COMMON /VALW2/W2                                                  APP23660
      COMMON /VALW3/W3                                                  APP23670
      COMMON /VALW4/W4                                                  APP23680
      COMMON /A2MCMX/RIYYNA                                             APP23690
      COMMON /A2MCMY/RIXXNA                                             APP23700
      COMMON /HYMCMN/HMPN                                               APP23710
      COMMON /HYMCML/HMPL                                               APP23720
      COMMON /CFGEMN/CMCBN                                              APP23730
      COMMON /CFGEML/CMCBL                                              APP23740
      COMMON /CFGFC/BIGNO                                               APP23750
      COMMON /STRES1/SIG1                                               APP23760
      COMMON /STRES2/SIG2                                               APP23770
      COMMON /STRES3/SIG3                                               APP23780
      COMMON /STRES4/SIG4                                               APP23790
C                                                                       APP23800
C     CALCULATE DIRECT STRESS (LBF/FT**2) DUE TO CENTRIFUGAL FORCE FOR  APP23810
C     BLADE SECTIONS ALONG THE PROPELLER RADIUS                         APP23820
C                                                                       APP23830
      DO 1 IR=2,9                                                       APP23840
         SIGCF(IR)=BIGNO(IR)/AREA(IR)                                   APP23850
```

```
    1 CONTINUE
C
C     CALCULATE TOTAL BENDING MOMENT COMPONENT (FT-LBF), PARALLEL TO
C     PITCH REFERENCE (CHORD) LINE, IMPOSED BY HYDRODYNAMIC AND
C     CENTRIFUGAL LOADING
C
      DO 2 IR=2,9
           TOTBMN(IR)=HMPN(IR)+CMCBN(IR)
    2 CONTINUE
C
C     CALCULATE TOTAL BENDING MOMENT COMPONENT (FT-LBF), NORMAL TO
C     PITCH REFERENCE (CHORD) LINE, IMPOSED BY HYDRODYNAMIC AND
C     CENTRIFUGAL LOADING
C
      DO 3 IR=2,9
           TOTBML(IR)=HMPL(IR)+CMCBL(IR)
    3 CONTINUE
C
C     CALCULATE STRESSES (LBF/FT**2) AT CRITICAL POINTS 1, 2, 3 AND 4
C     ALONG THE PROPELLER RADIUS USING RELATION (105), REF 8 , WHERE...
C
C     SIG1(IR)          DIRECT STRESS AT CRITICAL POINT 1 SPECIFIED BY
C                       BLADE SECTION COORDINATES ( W1, U1)
C     SIG2(IR)          DIRECT STRESS AT CRITICAL POINT 2 SPECIFIED BY
C                       BLADE SECTION COORDINATES ( W2, U2)
C     SIG3(IR)          DIRECT STRESS AT CRITICAL POINT 3 SPECIFIED BY
C                       BLADE SECTION COORDINATES ( W3, U3)
C     SIG4(IR)          DIRECT STRESS AT CRITICAL POINT 4 SPECIFIED BY
C                       BLADE SECTION COORDINATES ( W4, U4)
C
      DO 4 IR=2,9
           SIG1(IR)=SIGCF(IR)+((TOTBML(IR)*(-W1(IR)))/RIYYNA(IR))+
     1                        ((TOTBMN(IR)*(-U1(IR)))/RIXXNA(IR))
           SIG2(IR)=SIGCF(IR)+((TOTBML(IR)*(-W2(IR)))/RIYYNA(IR))+
     1                        ((TOTBMN(IR)*(-U2(IR)))/RIXXNA(IR))
           SIG3(IR)=SIGCF(IR)+((TOTBML(IR)*(-W3(IR)))/RIYYNA(IR))+
     1                        ((TOTBMN(IR)*(-U3(IR)))/RIXXNA(IR))
           SIG4(IR)=SIGCF(IR)+((TOTBML(IR)*(-W4(IR)))/RIYYNA(IR))+
     1                        ((TOTBMN(IR)*(-U4(IR)))/RIXXNA(IR))
    4 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STRCNA(KQ,C75R,SCSTRS)                                 APP24300
C                                                                       APP24310
C     INPUT              OUTPUT                DEFINITION               APP24320
C                                                                       APP24330
C     PROMAT                                   PROPELLER MATERIAL IDENTIFIER  APP24340
C                                                 1: CAST IRON          APP24350
C                                                 2: CAST STEEL         APP24360
C                                                 3: TYPE 2 BRONZE      APP24370
C                                                 4: TYPE 4 NI-AL BRONZE APP24380
C                                                 5: STAINLESS STEEL    APP24390
C     DIA                                      PROPELLER DIAMETER (FT)  APP24400
C     N                                        PROPELLER REVOLUTION RATE (RPM)APP24410
C     PDIVD                                    PITCH-DIAMETER RATIO     APP24420
C     KQ                                       TORQUE COEFFICIENT       APP24430
C     C75R                                     CHORD LENGTH 3/4 RADIUS (FT)  APP24440
C     NOSCRW                                   NO. OF PROPELLERS        APP24450
C     TC75R                                    BLADE THICKNESS-TO-CHORD RATIO  APP24460
C                                              3/4 RADIUS               APP24470
C                        SCSTRS                CONSTRAINT VARIABLE FOR BLADE  APP24480
C                                              THICKNESS-TO-CHORD RATIO 3/4   APP24490
C                                              RADIUS CONSTRAINT (TCSTRS<0)   APP24500
C                                                                       APP24510
      REAL*4  ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,             APP24520
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,    APP24530
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,                           APP24540
     3        VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,              APP24550
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SCSTRS,          APP24560
     5        C75R,KQ,PII,SC,CABSRB,PABSRB,FAC1D,FAC2D,FAC1N,T75MIN     APP24570
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP24580
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP24590
     2AEAOCV,TCSTRS,RJ                                                  APP24600
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA, APP24610
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP24620
      PII=3.141592654                                                   APP24630
C                                                                       APP24640
C     DETERMINE MAXIMUM ALLOWABLE STRESS (PSI) BASED ON NUMBER OF PRO-  APP24650
C     PELLERS AND MATERIAL IDENTIFIER                                   APP24660
C                                                                       APP24670
      IF(.NOT.(NOSCRW.EQ.1.0)) GO TO 1                                  APP24680
         IF(PROMAT.EQ.1.0)SC=3600.0                                     APP24690
         IF(PROMAT.EQ.2.0)SC=5915.0                                     APP24700
         IF(PROMAT.EQ.3.0)SC=7200.0                                     APP24710
         IF(PROMAT.EQ.4.0)SC=8910.0                                     APP24720
         IF(PROMAT.EQ.5.0)SC=5400.0                                     APP24730
      GO TO 2                                                           APP24740
    1 CONTINUE                                                          APP24750
         IF(PROMAT.EQ.1.0)SC=3950.0                                     APP24760
         IF(PROMAT.EQ.2.0)SC=6265.0                                     APP24770
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      IF(PROMAT.EQ.3.0)SC=7585.0
      IF(PROMAT.EQ.4.0)SC=9430.0
      IF(PROMAT.EQ.5.0)SC=5500.0
    2 CONTINUE
C
C     DETERMINE ABSORBED POWER FOR EACH PROPELLER
C
      QABSRB=ABS(KQ*WATRC*(DIA**5)*((N/60.0)**2))
      PABSRB=(2.0*PII*QABSRB*N)/33000.0
C
C     CALCULATE MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4
C     BLADE RADIUS USING RELATION (16), REF 2
C
      FAC1D=SC+(((DIA*N)**2)/(12.788))
      FAC2D=4.123*N*(DIA**3)
      FAC1N=(2375.0-(1125.0*PDIVD))*PABSRB
      T75MIN=((((FAC1N/(FAC2D*FAC1D))**0.33333)*0.21)+0.0028)*DIA
      TC75MN=T75MIN/C75R
C
C     DETERMINE CONSTRAINT VARIABLE FOR BLADE THICKNESS-TO-CHORD RATIO
C     CONSTRAINT
C
      SCSTRS=(TC75MN/TC75R)-1.0
      RETURN
      END
```

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      SUBROUTINE STRCNK(KQ,KT,C75R,SCSTRS)                              APP25050
C                                                                       APP25060
C     SUBROUTINE: STRCNK                 DATE OF LAST REVISION: APR 83  APP25070
C                                                                       APP25080
C     INPUT          OUTPUT              DEFINITION                     APP25090
C                                                                       APP25100
C     PRCMAT                             PROPELLER MATERIAL IDENTIFIER  APP25110
C                                            1: CAST IRON               APP25120
C                                            2: CAST STEEL              APP25130
C                                            3: TYPE 2 BRONZE           APP25140
C                                            4: TYPE 4 NI-AL BRONZE     APP25150
C                                            5: STAINLESS STEEL         APP25160
C     DIA                                PROPELLER DIAMETER (FT)        APP25170
C     N                                  PROPELLER REVOLUTION RATE (RPM)APP25180
C     PDIVD                              PITCH-DIAMETER RATIO           APP25190
C     AEDVAO                             EXPANDED AREA RATIO            APP25200
C     KQ                                 TORQUE COEFFICIENT             APP25210
C     KT                                 THRUST COEFFICIENT             APP25220
C     C75R                               CHORD LENGTH 3/4 RADIUS (FT)   APP25230
C     NOSCRW                             NO. OF PROPELLERS              APP25240
C     TC75R                              BLADE THICKNESS-TO-CHORD RATIO APP25250
C                                        3/4 RADIUS                     APP25260
C                    SCSTRS              CONSTRAINT VARIABLE FOR BLADE  APP25270
C                                        THICKNESS-TO-CHORD RATIO 3/4   APP25280
C                                        RADIUS CONSTRAINT (SCSTRS<0)   APP25290
C                                                                       APP25300
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,              APP25310
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,     APP25320
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,                               APP25330
     3       VK,TC,WT,Z,WATRC,WATNU,TEMP,NOSCRW,HCL,PATM,               APP25340
     4       PWATVA,PRCMAT,DIALIM,ETARR,                                APP25350
     5       RJ,C75R,R75R,KT,KQ                                         APP25360
      REAL*4 T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,T90R,    APP25370
     1       T100R,RAT                                                  APP25380
      REAL*4 CR(10),AR(10),BR(10),PLF(10),PLA(10),TR(10),V1F(10,11),    APP25390
     1       V2F(10,11),V1A(10,10),V2A(10,10),YFACE(11),YBACK(11),      APP25400
     2       HA(10),Y(11),DELPA(10),AA(10),DLFASM,XA(10),YA(10),SUMAA,  APP25410
     3       SUMAXA,SUMAYA,SMAX2A,SMAY2A,HF(11),DELPF(11),AF(11),DLPFSM,APP25420
     4       XF(11),YF(11),SUMAF,SUMAXF,SUMAYF,SMAX2F,SMAY2F,AREA(10),  APP25430
     5       XMT(10),YPRL(10),RIXXNA(10),RIYYNA(10),XCG(10),YCG(10)     APP25440
      REAL*4 U1(10),U2(10),U3(10),U4(10),W1(10),W2(10),W3(10),W4(10),   APP25450
     1       YBK,YFC                                                    APP25460
      REAL*4 HMPN(10),HMPL(10),CMCBN(10),CMCBL(10),BIGNO(10),SIG1(10),  APP25470
     1       SIG2(10),SIG3(10),SIG4(10),TC75MN,TC75WS,SCSTRS,SC         APP25480
      INTEGER*4 IF,KOUNT                                                APP25490
      LOGICAL OKAY1,OKAY2,OKAY3,OKAY4                                   APP25500
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP25510
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP25520
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     2AEACCV,TCSTFS,RJ                                                    APP25530
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNL,TEMP,NOSCRW,HCL,PATM,PWATVA,  APP25540
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                                APP25550
      COMMON /THICD/TCOR,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,   APP25560
     1T90R,T1CCR,FAT                                                      APP25570
      COMMON /AREELD/AREA                                                 APP25580
      COMMON /CGX/XCG                                                     APP25590
      COMMON /CGY/YCG                                                     APP25600
      COMMON /CRDLNT/CR                                                   APP25610
      COMMON /VALL1/U1                                                    APP25620
      COMMON /VALL2/U2                                                    APP25630
      COMMON /VALL3/U3                                                    APP25640
      COMMON /VALL4/U4                                                    APP25650
      COMMON /VALW1/W1                                                    APP25660
      COMMON /VALW2/W2                                                    APP25670
      COMMON /VALW3/W3                                                    APP25680
      COMMON /VALW4/W4                                                    APP25690
      COMMON /A2MCMX/RIYYNA                                               APP25700
      COMMON /A2MCMY/RIXXNA                                               APP25710
      COMMON /HYMCMN/HMPN                                                 APP25720
      COMMON /HYMCML/HMPL                                                 APP25730
      COMMON /CFGEMN/CMCBN                                                APP25740
      COMMON /CFGEML/CMCBL                                                APP25750
      COMMON /CFGFD/BIGNO                                                 APP25760
      COMMON /STRES1/SIG1                                                 APP25770
      COMMON /STRES2/SIG2                                                 APP25780
      COMMON /STRES3/SIG3                                                 APP25790
      COMMON /STRES4/SIG4                                                 APP25800
C                                                                         APP25810
C     DETERMINE MAXIMUM ALLOWABLE STRESS (PSI) BASED UPON THE NUMBER OF   APP25820
C     PROPELLERS AND TYPE OF MATERIAL                                     APP25830
C                                                                         APP25840
      IF(.NOT.(NOSCRW.EQ.1.0)) GO TO 1                                    APP25850
            IF(PROMAT.EQ.1.0)SC=3600.0                                    APP25860
            IF(PROMAT.EQ.2.0)SC=5915.0                                    APP25870
            IF(PROMAT.EQ.3.0)SC=7200.0                                    APP25880
            IF(PROMAT.EQ.4.0)SC=8910.0                                    APP25890
            IF(PROMAT.EQ.5.0)SC=5400.0                                    APP25900
      GO TO 2                                                             APP25910
    1 CONTINUE                                                            APP25920
            IF(PROMAT.EQ.1.0)SC=3950.0                                    APP25930
            IF(PROMAT.EQ.2.0)SC=6265.0                                    APP25940
            IF(PROMAT.EQ.3.0)SC=7585.0                                    APP25950
            IF(PROMAT.EQ.4.0)SC=9430.0                                    APP25960
            IF(PROMAT.EQ.5.0)SC=5500.0                                    APP25970
    2 CONTINUE                                                            APP25980
C                                                                         APP25990
C     INITIALIZE MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4   APP26000
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C        PROPELLER RADIUS TO A PERCENTAGE OF THE RATIO FOR THE SERIES      APP26010
C        PROPELLER USING RELATION (11), REF 2                              APP26020
C                                                                          APP26030
         TC75MN= ((0.0185-(0.00125*Z))*Z)/(2.073*AEDVAO)                   APP26040
C                                                                          APP26050
C        ITERATE FOR MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD RATIO AT 3/4APP26060
C        PROPELLER RADIUS BASED UPON THE CRITERIA THAT THE DIRECT STRESSES APP26070
C        CALCULATED AT CRITICAL POINTS 1 (W1,U1), 2 (W2,U2), 3 (W3,U3) AND APP26080
C        4 (W4,U4) DO NOT EXCEED THE MAXIMUM ALLOWBALE STRESS AS PREVIOUSLYAPP26090
C        DETERMINED. ITERATE FOR A MAXIMUM OF 100 TIMES.                   APP26100
C                                                                          APP26110
         KOUNT=0                                                           APP26120
       3 CONTINUE                                                          APP26130
              TC75MN=TC75MN+0.0010                                         APP26140
              KOUNT=KOUNT+1                                                APP26150
CC                                                                         APP26160
CC            CALCULATE MAXIMUM BLADE SECTION THICKNESS DISTRIBUTION ALONG APP26170
CC            THE PROPELLER RADIUS                                         APP26180
CC                                                                         APP26190
              CALL TDIST(C75R,TC75MN,DIA,Z,AEDVAO)                         APP26200
CC                                                                         APP26210
CC            DETERMINE BLADE SECTION PROPERTIES                           APP26220
CC                                                                         APP26230
              CALL BLDPRP                                                  APP26240
CC                                                                         APP26250
CC            DETERMINE BENDING MOMENTS DUE TO HYDRODYNAMIC LOADING        APP26260
CC                                                                         APP26270
              CALL HYDLD(KQ,KT)                                            APP26280
CC                                                                         APP26290
CC            DETERMINE FORCE AND BENDING MOMENTS DUE TO CENTRIFUGAL       APP26300
CC            LOADING                                                      APP26310
CC                                                                         APP26320
              CALL CNFGLD                                                  APP26330
CC                                                                         APP26340
CC            DETERMINE STRESS (LBF/FT2) AT CRITICAL POINTS 1,2,3,4        APP26350
CC                                                                         APP26360
              CALL SIGNDS                                                  APP26370
CC                                                                         APP26380
CC            INITIALIZE LOGICAL VARIABLES FOR CURRENT ITERATION           APP26390
CC                                                                         APP26400
              OKAY1=.TRUE.                                                 APP26410
              OKAY2=.TRUE.                                                 APP26420
              OKAY3=.TRUE.                                                 APP26430
              OKAY4=.TRUE.                                                 APP26440
CC                                                                         APP26450
CC            CHECK STRESSES AT CRITICAL POINTS 1,2,3, AND 4 TO DETERMINE  APP26460
CC            WHETHER OR NOT MAXIMUM ALLOWABLE STRESS IS EXCEEDED          APP26470
CC                                                                         APP26480
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      DO 8 IR=2,9                                                       APP26490
            IF(.NOT.(ABS(SIG1(IR)).GE.(SC*144.0)))GO TO 4               APP26500
                  OKAY1=.FALSE.                                         APP26510
    4       CONTINUE                                                    APP26520
            IF(.NOT.(ABS(SIG2(IR)).GE.(SC*144.0)))GO TO 5               APP26530
                  OKAY2=.FALSE.                                         APP26540
    5       CONTINUE                                                    APP26550
            IF(.NOT.(ABS(SIG3(IR)).GE.(SC*144.0)))GO TO 6               APP26560
                  OKAY3=.FALSE.                                         APP26570
    6       CONTINUE                                                    APP26580
            IF(.NOT.(ABS(SIG4(IR)).GE.(SC*144.0)))GO TO 7               APP26590
                  OKAY4=.FALSE.                                         APP26600
    7       CONTINUE                                                    APP26610
    8 CONTINUE                                                          APP26620
C     IF(.NOT.((OKAY1).AND.(OKAY2).AND.(OKAY3).AND.(OKAY4)))GO TO 3     APP26630
      IF(.NOT.(((OKAY1).AND.(OKAY2).AND.(OKAY3).AND.(OKAY4)).OR.        APP26640
     1         (KOUNT.EQ.100)))GO TO 3                                  APP26650
C                                                                       APP26660
C     HAVING DETERMINED MINIMUM REQUIRED BLADE THICKNESS-TO-CHORD       APP26670
C     RATIO AT 3/4 PROPELLER RADIUS, CALCULATE CONSTRAINT VARIABLE      APP26680
C                                                                       APP26690
      SCSTRS=(TC75MN/TC75R)-1.0                                         APP26700
      RETURN                                                            APP26710
      END                                                               APP26720
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      SUBROUTINE TDIST(C75R,TC75R,DIA,Z,AEDVAC)                         APP26750
C                                                                       APP26760
C                                                                       APP26770
C     SUBROUTINE:  TDIST                      DATE OF LAST REVISION: MAR 83 APP26780
C                                                                       APP26790
C     INPUT               OUTPUT              DEFINITION                APP26800
C                                                                       APP26810
C     C75R                                    CHORD LENGTH AT 3/4 RADIUS APP26820
C                                             (FEET)                    APP26830
C     TC75R                                   BLADE SECTION THICKNESS-TO- APP26840
C                                             CHORD RATIO AT 3/4 RADIUS APP26850
C     DIA                                     PROPELLER DIAMETER (FEET) APP26860
C     Z                                       NO. OF PROPELLER BLADES   APP26870
C     AEDVAO                                  EXPANDED AREA RATIO       APP26880
C                         COMMON /THICD/      BLADE SECTION MAXIMUM     APP26890
C                                             THICKNESSESS ALONG PROPELLER APP26900
C                                             RADIUS (FEET)             APP26910
      REAL*4 T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,T90R,    APP26920
     1        T100R,RAT,C75R,TC75R,DIA,Z,AEDVAC,T75RWS                  APP26930
      COMMON /THICD/T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,  APP26940
     1T90R,T100R,RAT                                                    APP26950
C                                                                       APP26960
C     CALCULATE MAXIMUM THICKNESS AT 3/4 RADIUS                         APP26970
C                                                                       APP26980
      T75R=TC75R*C75R                                                   APP26990
C                                                                       APP27000
C     CALCULATE MAXIMUM THICKNESS AT 3/4 RADIUS FOR SERIES PROPELLER    APP27010
C     USING RELATION (11), REF 2                                        APP27020
C                                                                       APP27030
      T75RWS=DIA*(0.0185-(0.00125*Z))                                   APP27040
C                                                                       APP27050
C     CALCULATE RATIO OF MAXIMUM THICKNESSES AT 3/4 RADIUS              APP27060
C                                                                       APP27070
      RAT=T75R/T75RWS                                                   APP27080
C                                                                       APP27090
C     GENERATE A DISTRIBUTION OF BLADE SECTION MAXIMUM THICKNESSES ALONGAPP27100
C     THE PROPELLER RADIUS BASED ON THE RATIO CALCULATED ABOVE          APP27110
C                                                                       APP27120
      IF(.NOT.(Z.EQ.3.0))GO TO 1                                        APP27130
            T00R=0.0500*DIA                                             APP27140
            T1XR=RAT*DIA*(0.05384-(0.0041*Z))                           APP27150
      GO TO 5                                                           APP27160
    1 CONTINUE                                                          APP27170
      IF(.NOT.(Z.EQ.4.0))GO TO 2                                        APP27180
            T00R=0.045*DIA                                              APP27190
            T1XR=RAT*DIA*(0.054646-(0.004165*Z))                        APP27200
      GO TO 5                                                           APP27210
    2 CONTINUE                                                          APP27220
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      IF(.NOT.(Z.EQ.5.0))GO TO 3                                       APP27230
           TCCR=0.040*DIA                                               APP27240
           T1XR=RAT*DIA*(0.054646-(0.004165*Z))                         APP27250
      GO TO 5                                                           APP27260
    3 CONTINUE                                                          APP27270
      IF(.NOT.(Z.EQ.6))GO TO 4                                          APP27280
           TCCR=0.035*DIA                                               APP27290
           T1XR=RAT*DIA*(C.054646-(0.004165*Z))                         APP27300
      GO TO 5                                                           APP27310
    4 CONTINUE                                                          APP27320
           TCCR=0.035*DIA                                               APP27330
           T1XR=RAT*DIA*(0.05384-(0.0041*Z))                            APP27340
    5 CONTINUE                                                          APP27350
      T20R=RAT*DIA*(0.0526-(0.0040*Z))                                  APP27360
      T30R=RAT*DIA*(0.0464-(0.0035*Z))                                  APP27370
      T40R=RAT*DIA*(0.0402-(0.0030*Z))                                  APP27380
      T50R=RAT*DIA*(0.0340-(0.0025*Z))                                  APP27390
      T6CR=RAT*DIA*(0.0278-(C.0020*Z))                                  APP27400
      T70R=RAT*DIA*(0.0216-(0.0015*Z))                                  APP27410
      T80R=RAT*DIA*(0.0154-(0.0010*Z))                                  APP27420
      T90R=RAT*DIA*(0.0092-(0.0005*Z))                                  APP27430
      T100R=RAT*DIA*(0.0030-(0.0000*Z))                                 APP27440
      RETURN                                                            APP27450
      END                                                               APP27460
```

```
      SUBROUTINE WGTCAL(C75R)                                           APP27490
C                                                                       APP27500
C     SUBROUTINE:  WGTCAL                  DATE OF LAST REVISION: MAR 83 APP27510
C                                                                       APP27520
C     INPUT              OUTPUT            DEFINITION                   APP27530
C                                                                       APP27540
C     AEDVAO                               EXPANDED AREA RATIO          APP27550
C     C75R                                 CHORD LENGTH AT 3/4 RADIUS   APP27560
C                                          (FEET)                       APP27570
C     DIA                                  PROPELLER DIAMETER (FEET)    APP27580
C     PRCMAT                               PROPELLER MATERIAL IDENTIFIER APP27590
C                                             1: CAST IRON              APP27600
C                                             2: CAST STEEL             APP27610
C                                             3: TYPE 2 BRONZE          APP27620
C                                             4: TYPE 4 NI-AL BRONZE    APP27630
C                                             5: STAINLESS STEEL        APP27640
C     TC75R                                BLADE SECTION THICKNESS-TO-  APP27650
C                                          CHORD RATIO AT 3/4 RADIUS    APP27660
C     Z                                    NO. OF PROPELLER BLADES      APP27670
C                        WEIGHT            PROPELLER BLADE WEIGHT (LBF) APP27680
C                                                                       APP27690
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,              APP27700
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,     APP27710
     2       PCWBAL,DIACNU,AEAOCV,TCSTRS,                               APP27720
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,               APP27730
     4       PWATVA,PRCMAT,DIALIM,ETARR,                                APP27740
     5       RJ,C75R,R75R,KT,KQ                                         APP27750
      REAL*4 T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,T90R,    APP27760
     1       T100R,RAT                                                  APP27770
      REAL*4 CR(10),AR(10),BR(10),PLF(10),PLA(10),TR(10),V1F(10,11),    APP27780
     1       V2F(10,11),V1A(10,10),V2A(10,10),YFACE(11),YBACK(11),      APP27790
     2       HA(10),Y(11),DELPA(10),AA(10),DLFASM,XA(10),YA(10),SUMAA,  APP27800
     3       SUMAXA,SUMAYA,SMAX2A,SMAY2A,HF(11),DELPF(11),AF(11),DLPFSM,APP27810
     4       XF(11),YF(11),SUMAF,SUMAXF,SUMAYF,SMAX2F,SMAY2F,AREA(10),  APP27820
     5       XMT(10),YPRL(10),RIXXNA(10),RIYYNA(10),XCG(10),YCG(10)     APP27830
      REAL*4 U1(10),U2(10),U3(10),U4(10),W1(10),W2(10),W3(10),W4(10),   APP27840
     1       YBK,YFC                                                    APP27850
      REAL*4 WC,VCLBLD                                                  APP27860
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,APP27870
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,    APP27880
     2AEAOCV,TCSTRS,RJ                                                  APP27890
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA, APP27900
     1PRCMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC                              APP27910
      COMMON /THICC/T00R,T1XR,T20R,T30R,T40R,T50R,T60R,T70R,T75R,T80R,  APP27920
     1T90R,T100R,RAT                                                    APP27930
      COMMON /AREBLD/AREA                                               APP27940
      COMMON /CGX/XCG                                                   APP27950
      COMMON /CGY/YCG                                                   APP27960
```

```
      COMMON /CRDINT/CR
      COMMON /VALU1/U1
      COMMON /VALU2/U2
      COMMON /VALU3/U3
      COMMON /VALU4/U4
      COMMON /VALW1/W1
      COMMON /VALW2/W2
      COMMON /VALW3/W3
      COMMON /VALW4/W4
      COMMON /A2MCMX/RIYYNA
      COMMON /A2MCMY/RIXXNA
C
C     DETERMINE BLADE SECTION MAXIMUM THICKNESS DISTRIBUTION
C
      CALL TDIST(C75R,TC75R,DIA,Z,AEDVAC)
C
C     DETERMINE BLADE SECTION PROPERTIES
C
      CALL BLDPRP
C
C     DETERMINE VOLUME OF A PROPELLER BLADE
C
      CALL BLDVOL(VOLBLD)
C
C     SPECIFY WEIGHT DENSITY OF MATERIAL SELECTED WHERE...
C
C     PROMAT        MATERIAL               WEIGHT DENSITY (LBF/IN**3)
C       1           CAST IRON               .260
C       2           CAST STEEL              .284
C       3           TYPE 2 BRONZE           .305
C       4           TYPE 4 NI-AL BRONZE     .278
C       5           STAINLESS STEEL         .283
C
      IF(PROMAT.EQ.1.0)WD=.260
      IF(PROMAT.EQ.2.0)WD=.284
      IF(PROMAT.EQ.3.0)WD=.305
      IF(PROMAT.EQ.4.0)WD=.278
      IF(PROMAT.EQ.5.0)WD=.283
C
C     CALCULATE PROPELLER BLADE WEIGHT
C
      WEIGHT=VOLBLD*WD*(1728.0)
      RETURN
      END
```

APPENDIX C

ANALIZ CODES--DESIGN CASE NO. 1

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 1" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=59.0
           WATRO=1.9384
           WATNU=.0000122850
           PATM=14.7
           PWATVA=.247
CC
CC         PROPELLER PARAMETERS
CC
           Z=5.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TD=0.19
           ETARR=1.025
           NCSCRW=1.0
           HCL=19.0
           DIALIM=22.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR 'DESIGN CASE 1"
CC
```

```
      PE=18153.0
      VK=24.0
      V=1.688*VK
      AEDVAO=0.85
      DIA=22.0
      TC75R=((0.0185-0.00125*Z)*Z)/(2.073*AEDVAO)
CC
      END OF INPUT-INITIALIZATION PHASE
CC
   GO TO 3
C
   EXECUTION PHASE
C
 1 CONTINUE
   IF(.NOT.(ICALC.EQ.2))GO TO 2
      CALL RNCAL(N)
      CALL CH75RA(C75R)
      CALL REY75R(C75R,R75R)
      CALL COEFSA(RJ,R75R,KT,KQ)
      CALL OPWEFF(RJ,KT,KQ,ETAO)
      CALL CALCQS(KQ,QS)
      CALL JCNA(RJ,RJCNL,RJCNU)
      CALL REYCNA(R75R,R75RCL,R75RCU)
      CALL EXTCCN(Z,AEDVAO,TC75R,AEACCL,AEADCU,TC75CL,TC75CU)
      CALL BLPOW1(KT,POWBAL)
      CALL DICNUA(DIACNU)
      CALL CAVCNA(KT,AEAOCV)
      CALL STRCNA(KQ,C75R,TCSTRS)
CC
      END OF EXECUTION PHASE
CC
   GO TO 3
 2 CONTINUE
C
   OUTPUT-RESULT PHASE
C
      PD=(2.0*PII*QS*N)/33000.0
      WRITE(6,9000)
      WRITE(6,9001)
      WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
      WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
      WRITE(6,9004)Z
      IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
         WRITE(6,9005)SC
      GO TO 86
81    CONTINUE
      IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
         WRITE(6,9006)SC
```

```
      GO TO 86
82    CONTINUE
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83
           WRITE(6,9007)SC
      GO TO 86
83    CONTINUE
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84
           WRITE(6,9008)SC
      GO TO 86
84    CONTINUE
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85
           WRITE(6,9009)SC
      GO TO 86
85    CONTINUE
           WRITE(6,9010)
86    CONTINUE
      WRITE(6,9011)PE,V,N,QS,PD,KJ,KT,KQ,ETAC,R75R,DIA,PDIVD,
     1              AEDVAO,TC75R
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN
    3 CONTINUE
      RETURN
C
C     MISCELLANEOUS FORMAT STATEMENTS
C
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1',/,
     1       1X,'                             SUBROUTINE "STRGNA"',///)
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  PE,V,AEDVAO,DIA,TC75R',//)
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',
     1       F10.4,/,
     1       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,
     2       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,
     3       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,
     4       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,///)
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,///)
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',
     1       F10.1)
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,
```

```
     1           1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP01450
9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,               APP01460
     1           1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP01470
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)                APP01480
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,            APP01490
     2           1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                        APP01500
     3           1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                        APP01510
     4           1X,29X,'QS (FT-LBF)',23X,'=',F12.1,/,                        APP01520
     4           1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                       APP01530
     4           1X,29X,'J          ',23X,'=',F10.4,/,                        APP01540
     4           1X,29X,'KT         ',23X,'=',F10.4,/,                        APP01550
     4           1X,29X,'KQ         ',23X,'=',F10.4,/,                        APP01560
     4           1X,29X,'ETAC       ',23X,'=',F10.4,/,                        APP01570
     5           1X,29X,'REY75R     ',23X,'=',E10.1,/,                        APP01580
     6           1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                        APP01590
     7           1X,29X,'P/D        ',23X,'=',F10.4,/,                        APP01600
     9           1X,29X,'AE/AO      ',23X,'=',F10.4,/,                        APP01610
     8           1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)                       APP01620
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,      APP01630
     1           1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                          APP01640
     2           1X,29X,'MIN T/C .75R',22X,'=',F10.6)                         APP01650
      END                                                                     APP01660
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC          SET "DESIGN CASE 1" PARAMETERS
CC
CC          ENVIRONMENTAL
CC
            TEMP=59.0
            WATRO=1.9384
            WATNU=.0000122850
            PATM=14.7
            PWATVA=.247
CC
CC          PROPELLER PARAMETERS
CC
            Z=5.0
            PROMAT=5.0
CC
CC          HULL PARAMETERS
CC
            WT=0.22
            TD=0.19
            ETARR=1.025
            NOSCRW=1.0
            HCL=19.0
            DIALIM=22.0
CC
CC          SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"
CC
```

```
      PE=18153.0
      VK=24.0
      V=1.688*VK
      AEDVAO=0.85
      DIA=22.0
      TC75R=((0.0185-0.00125*Z)*Z)/(2.073*AEDVAO)
CC
CC          END OF INPUT-INITIALIZATION PHASE
CC
      GO TO 3
C
C     EXECUTION PHASE
C
    1 CONTINUE
      IF(.NOT.(ICALC.EQ.2))GO TO 2
            CALL RNCAL(N)
            CALL CH75RA(C75R)
            CALL REY75R(C75R,R75R)
            CALL COEFSA(RJ,R75R,KT,KQ)
            CALL OFWEFF(RJ,KT,KQ,ETAO)
            CALL CALCQS(KQ,QS)
            CALL JCNA(RJ,RJCNL,RJCNU)
            CALL REYCNA(R75R,R75RCL,R75RCU)
            CALL EXTCCN(Z,AEDVAO,TC75R,AEACCL,AEAOCU,TC75CL,TC75CU)
            CALL BLPOW1(KT,POWBAL)
            CALL DICNUA(DIACNL)
            CALL CAVCNA(KT,AEAOCV)
            CALL STRCNK(KQ,KT,C75R,TCSTRS)
CC
CC          END OF EXECUTION PHASE
CC
      GO TO 3
    2 CONTINUE
C
C     OUTPUT-RESULT PHASE
C
            PD=(2.0*PII*QS*N)/33000.0
            WRITE(6,9000)
            WRITE(6,9001)
            WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
            WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
            WRITE(6,9004)Z
            IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
                 WRITE(6,9005)SC
            GO TO 86
   81       CONTINUE
            IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
                 WRITE(6,9006)SC
```

```
      GO TO 86
   82 CONTINUE
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83
         WRITE(6,9007)SC
      GO TO 86
   83 CONTINUE
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84
         WRITE(6,9008)SC
      GO TO 86
   84 CONTINUE
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85
         WRITE(6,9009)SC
      GO TO 86
   85 CONTINUE
         WRITE(6,9010)
   86 CONTINUE
      WRITE(6,9011)PE,V,N,QS,PD,RJ,KT,KQ,ETAC,R75R,DIA,PDIVD,
     1                   AEDVAC,TC75R
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN
    3 CONTINUE
      RETURN
C
C     MISCELLANEOUS FORMAT STATEMENTS
C
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1',/,
     1      1X,'                                  SUBROUTINE "STRCNK"',//)
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  PE,V,AEDVAC,DIA,TC75R',/)
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',
     1      F10.4,/,
     1      1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,
     2      1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,
     3      1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,
     4      1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,
     1      1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,
     2      1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,
     3      1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,
     4      1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,
     5      1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',
     1      F10.1)
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,
```

```
     1           1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP03130
9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,               APP03140
     1           1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP03150
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)                APP03160
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE  (HP)',27X,'=',F10.1,/,           APP03170
     2           1X,29X,'V   (FT/SEC)',23X,'=',F10.4,/,                      APP03180
     3           1X,29X,'N   (RPM)   ',23X,'=',F10.4,/,                      APP03190
     4           1X,29X,'CS  (FT-LBF)',23X,'=',F12.1,/,                      APP03200
     4           1X,29X,'PD   (HP)   ',23X,'=',F10.2,//,                     APP03210
     4           1X,29X,'J           ',23X,'=',F10.4,/,                      APP03220
     4           1X,29X,'KT          ',23X,'=',F10.4,/,                      APP03230
     4           1X,29X,'KQ          ',23X,'=',F10.4,/,                      APP03240
     4           1X,29X,'ETAO        ',23X,'=',F10.4,/,                      APP03250
     5           1X,29X,'REY75R      ',23X,'=',E10.1,/,                      APP03260
     6           1X,29X,'DIA  (FT)   ',23X,'=',F10.4,/,                      APP03270
     7           1X,29X,'P/D         ',23X,'=',F10.4,/,                      APP03280
     9           1X,29X,'AE/AO       ',23X,'=',F10.4,/,                      APP03290
     8           1X,29X,'T/C  .75R   ',23X,'=',F10.4,//)                     APP03300
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP03310
     1           1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                         APP03320
     2           1X,29X,'MIN T/C .75R',22X,'=',F10.6)                        APP03330
      END                                                                    APP03340
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEACCL,AEACCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KC,PD
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEACCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEACMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 1" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=59.0
           WATRO=1.9384
           WATNU=.000012285
           PATM=14.7
           PWATVA=.247
CC
CC         PROPELLER PARAMETERS
CC
           Z=5.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TD=0.19
           ETARR=1.025
           NCSCRW=1.0
           HCL=19.0
           DIALIM=22.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR 'DESIGN CASE 1"
CC
```

```
      PE=18153.0                                                        APP03850
      VK=24.0                                                           APP03860
      V=1.688*VK                                                        APP03870
CC                                                                      APP03880
CC    END OF INPUT-INITIALIZATION PHASE                                 APP03890
CC                                                                      APP03900
   GO TO 3                                                              APP03910
C                                                                       APP03920
C  EXECUTION PHASE                                                      APP03930
C                                                                       APP03940
 1 CONTINUE                                                             APP03950
   IF(.NOT.(ICALC.EQ.2))GO TO 2                                         APP03960
      CALL RNCAL(N)                                                     APP03970
      CALL CF75RA(C75R)                                                 APP03980
      CALL REY75R(C75R,R75R)                                            APP03990
      CALL COEFSA(RJ,R75R,KT,KQ)                                        APP04000
      CALL OPWEFF(RJ,KT,KQ,ETAO)                                        APP04010
      CALL CALCQS(KQ,QS)                                                APP04020
      CALL JCNA(RJ,RJCNL,RJCNU)                                         APP04030
      CALL REYCNA(R75R,R75RCL,R75RCU)                                   APP04040
      CALL EXTCCN(Z,AELVAO,TC75R,AEACCL,AEAOCU,TC75CL,TC75CU)           APP04050
      CALL BLPOW1(KT,POWBAL)                                            APP04060
      CALL DICNUA(DIACNU)                                               APP04070
      CALL CAVCNA(KT,AEACCV)                                            APP04080
      CALL STRCNA(KQ,C75R,TCSTRS)                                       APP04090
CC                                                                      APP04100
CC    END OF EXECUTION PHASE                                            APP04110
CC                                                                      APP04120
   GO TO 3                                                              APP04130
 2 CONTINUE                                                             APP04140
C                                                                       APP04150
C  OUTPUT-RESULT PHASE                                                  APP04160
C                                                                       APP04170
      PD=(2.0*PII*QS*N)/33000.0                                         APP04180
      WRITE(6,9000)                                                     APP04190
      WRITE(6,9001)                                                     APP04200
      WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA                         APP04210
      WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM                        APP04220
      WRITE(6,9004)Z                                                    APP04230
      IF(.NOT.(PROMAT.EQ.1.0))GO TO 81                                  APP04240
         WRITE(6,9005)SC                                                APP04250
      GO TO 86                                                          APP04260
81    CONTINUE                                                          APP04270
      IF(.NOT.(PROMAT.EQ.2.0))GO TO 82                                  APP04280
         WRITE(6,9006)SC                                                APP04290
      GO TO 86                                                          APP04300
82    CONTINUE                                                          APP04310
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83                                  APP04320
```

```
               WRITE(6,9007)SC                                                  APP04330
            GO TO 86                                                            APP04340
   83       CONTINUE                                                            APP04350
            IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                                    APP04360
               WRITE(6,9008)SC                                                  APP04370
            GO TO 86                                                            APP04380
   84       CONTINUE                                                            APP04390
            IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                                    APP04400
               WRITE(6,9009)SC                                                  APP04410
            GO TO 86                                                            APP04420
   85       CONTINUE                                                            APP04430
               WRITE(6,9010)                                                    APP04440
   86       CONTINUE                                                            APP04450
            WRITE(6,9011)PE,V,N,QS,PD,KJ,KT,KQ,ETAC,R75R,DIA,PDIVD,             APP04460
     1                   AEDVAC,TC75R                                           APP04470
            WRITE(6,9012)DIALIM,AEAOMN,TC75MN                                   APP04480
    3 CONTINUE                                                                  APP04490
      RETURN                                                                    APP04500
C                                                                               APP04510
C     MISCELLANEOUS FORMAT STATEMENTS                                           APP04520
C                                                                               APP04530
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1',/             APP04540
     1         1X,'                          SUBROUTINE "STRCNA"',//)           APP04550
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  PE,V',/)                          APP04560
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',            APP04570
     1         F10.4,/,                                                         APP04580
     1         1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,                 APP04590
     2         1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,                    APP04600
     3         1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,             APP04610
     4         1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)           APP04620
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,         APP04630
     1         1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,               APP04640
     2         1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,            APP04650
     3         1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,                   APP04660
     4         1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,          APP04670
     5         1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)                   APP04680
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',          APP04690
     1         F10.1)                                                           APP04700
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,                       APP04710
     1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)                 APP04720
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,                      APP04730
     1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)                 APP04740
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                          APP04750
     1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)                 APP04760
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,                    APP04770
     1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)                 APP04780
 9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,                 APP04790
     1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)                 APP04800
```

```
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NCT CONSIDERED',/)       APP04810
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,   APP04820
     2          1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,               APP04830
     3          1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,               APP04840
     4          1X,29X,'CS (FT-LBF)',23X,'=',F12.1,/,               APP04850
     4          1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,              APP04860
     4          1X,29X,'J          ',23X,'=',F10.4,/,               APP04870
     4          1X,29X,'KT         ',23X,'=',F10.4,/,               APP04880
     4          1X,29X,'KQ         ',23X,'=',F10.4,/,               APP04890
     4          1X,29X,'ETAO       ',23X,'=',F10.4,/,               APP04900
     5          1X,29X,'REY75R     ',23X,'=',E10.1,/,               APP04910
     6          1X,29X,'DIA  (FT)  ',23X,'=',F10.4,/,               APP04920
     7          1X,29X,'P/D        ',23X,'=',F10.4,/,               APP04930
     9          1X,29X,'AE/AC      ',23X,'=',F10.4,/,               APP04940
     8          1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)              APP04950
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP04960
     1          1X,29X,'MIN AE/AC',25X,'=',F10.4,/,                 APP04970
     2          1X,29X,'MIN T/C .75R',22X,'=',F10.6)                APP04980
      END                                                           APP04990
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEACCL,AEACCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEACCV,TCSTRS,RJ
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 1" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 1" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=59.0
           WATRO=1.9384
           WATNU=.00012285
           PATM=14.7
           PWATVA=.247
CC
CC         PROPELLER PARAMETERS
CC
           Z=5.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TC=0.19
           ETARR=1.025
           NCSCRW=1.0
           HCL=19.0
           DIALIM=22.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 1"
CC
```

```
      PE=18153.0
      VK=24.0
      V=1.688*VK
CC
CC       END OF INPUT-INITIALIZATION PHASE
CC
   GO TO 3
C
C  EXECUTION PHASE
C
 1 CONTINUE
   IF(.NOT.(ICALC.EQ.2))GO TO 2
         CALL RNCAL(N)
         CALL CH75RA(C75R)
         CALL REY75R(C75R,R75R)
         CALL COEFSA(RJ,R75R,KT,KQ)
         CALL OPWEFF(RJ,KT,KQ,ETAO)
         CALL CALCQS(KQ,QS)
         CALL JCNA(RJ,RJCNL,RJCNU)
         CALL REYCNA(R75R,R75RCL,R75RCU)
         CALL EXTCCN(Z,AEDVAO,TC75R,AEACCL,AEAOCU,TC75CL,TC75CU)
         CALL BLPOWI(KT,PCWBAL)
         CALL DICNUA(DIACNU)
         CALL CAVCNA(KT,AEACCV)
         CALL STRCNK(KQ,KT,C75R,TCSTRS)
CC
CC       END OF EXECUTION PHASE
CC
   GO TO 3
 2 CONTINUE
C
C  OUTPUT-RESULT PHASE
C
         PE=(2.0*PII*QS*N)/33000.0
         WRITE(6,9000)
         WRITE(6,9001)
         WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
         WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
         WRITE(6,9004)Z
         IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
             WRITE(6,9005)SC
         GO TO 86
  81     CONTINUE
         IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
             WRITE(6,9006)SC
         GO TO 86
  82     CONTINUE
         IF(.NOT.(PROMAT.EQ.3.0))GO TO 83
```

```
            WRITE(6,9007)SC                                               APP05980
         GO TO 86                                                         APP05990
   83    CONTINUE                                                         APP06000
         IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                                 APP06010
            WRITE(6,9008)SC                                               APP06020
         GO TO 86                                                         APP06030
   84    CONTINUE                                                         APP06040
         IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                                 APP06050
            WRITE(6,9009)SC                                               APP06060
         GO TO 86                                                         APP06070
   85    CONTINUE                                                         APP06080
            WRITE(6,9010)                                                 APP06090
   86    CONTINUE                                                         APP06100
         WRITE(6,9011)PE,V,N,QS,PD,RJ,KT,KC,ETAC,R75R,DIA,PDIVD,          APP06110
     1                AEDVAO,TC75R                                        APP06120
         WRITE(6,9012)DIALIM,AEAOMN,TC75MN                                APP06130
    3 CONTINUE                                                            APP06140
      RETURN                                                              APP06150
C                                                                         APP06160
C     MISCELLANEOUS FORMAT STATEMENTS                                     APP06170
C                                                                         APP06180
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1',/       APP06190
     1       1X,'                              SUBROUTINE "STRCNK"',//)   APP06200
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  PE,V',/)                    APP06210
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',      APP06220
     1       F10.4,/,                                                     APP06230
     1       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,             APP06240
     2       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,                APP06250
     3       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,         APP06260
     4       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)       APP06270
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,   APP06280
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,           APP06290
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,        APP06300
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,               APP06310
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,      APP06320
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)               APP06330
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',    APP06340
     1       F10.1)                                                       APP06350
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,                 APP06360
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP06370
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,                APP06380
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP06390
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                    APP06400
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP06410
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,              APP06420
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP06430
 9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,           APP06440
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP06450
```

```
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)          APP06460
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,      APP06470
     2      1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                       APP06480
     3      1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                       APP06490
     4      1X,29X,'QS (FT-LBF)',23X,'=',F12.1,/,                       APP06500
     4      1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                      APP06510
     4      1X,29X,'J          ',23X,'=',F10.4,/,                       APP06520
     4      1X,29X,'KT         ',23X,'=',F10.4,/,                       APP06530
     4      1X,29X,'KQ         ',23X,'=',F10.4,/,                       APP06540
     4      1X,29X,'ETAO       ',23X,'=',F10.4,/,                       APP06550
     5      1X,29X,'REY75R     ',23X,'=',E10.1,/,                       APP06560
     6      1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                       APP06570
     7      1X,29X,'P/D        ',23X,'=',F10.4,/,                       APP06580
     9      1X,29X,'AE/AO      ',23X,'=',F10.4,/,                       APP06590
     8      1X,29X,'T/C .75R   ',23X,'=',F10.4,//)                      APP06600
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP06610
     1      1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                         APP06620
     2      1X,29X,'MIN T/C .75R',22X,'=',F10.6)                        APP06630
      END                                                               APP06640
```

APPENDIX D

<u>CONTROL CARD IMAGES--DESIGN CASE NO. 1</u>

```
$A   TITLE
  WAGENINGEN B-SERIES PROPELLER CPTIMIZATICN
$B    NCALC        NDV         NSV       N2VAR    NXAPRX    IPNPUT     IPDBG
          2          2                                           0
$C   IPRINT      ITMAX      ICNDIR       NSCAL     ITRM     LINCBJ    NACMX1
          1       1C00                      -1                            15
$D1    FDCH       FDCHM         CT       CTMIN      CTL     CTLMIN     THETA
     C.0001      C.0C01
$D2  DELFUN      DABFUN      ALPHAX     ABCBJI

$E   NDVTOT        ICBJ      SGNCPT
          2           1         1.0
$F      VLB         VUB           X       SCAL
       0.01         1.8         0.1        1.0
        0.4         1.4         0.5        1.0
$G   NDSSGN       IDSGN       AMULT
          1          23         1.0
          2           7         1.0
$H    NCONS
          9
$I1    ICCN        JCON        LCCN
$I2      BL       SCAL1          BU      SCAL2
         11          11
-1.0    +16         1.0         C.C        1.0
         12          12
-1.0    +16         1.0         0.0        1.0
         13          13
-1.0    +16         1.0         0.0        1.0
         14          14
-1.0    +16         1.0         0.0        1.0
         15          15
-1.0    +16         1.0         C.0        1.0
         16          16
-1.0    +16         1.0         0.0        1.0
         17          17
-1.0    +16         1.0         0.0        1.0
         18          18
-1.0    +16         1.0         C.0        1.0
         19          19
-1.0    +16         1.0         C.0        1.0
$V
END
```

```
$A   TITLE
  WAGENINGEN  B-SERIES  PROPELLER  OPTIMIZATION
$B    NCALC        NDV         NSV       N2VAR      NXAPRX     IPNPUT      IPDBG
          2          5                                              0
$C   IPRINT      ITMAX      ICNDIR       NSCAL       ITRM     LINOBJ     NACMXI
          1       1000                      -1         30                    15
$D1    FDCH      FDCHM          CT       CTMIN        CTL     CTLMIN      THETA
     0.0001     0.0001
$D2  DELFUN     DABFUN      ALPHAX      ABOBJ1

$E   NDVTOT       IOBJ      SGNOPT
          5          1         1.0
$F      VLB        VUB           X        SCAL
        0.2        1.1        0.30         1.0
        1.0       50.0        30.0        10.0
       0.01        1.6         0.1         1.0
        0.4        1.4         0.5         1.0
      0.003        0.5      0.0300       0.010
$G   NDSSGN      IDSGN       AMULT
          1          3         1.0
          2          4         1.0
          3         23         1.0
          4          7         1.0
          5          9         1.0
$H    NCONS
         12
$I1    ICON       JCON        LCON
$I2      BL      SCAL1          BU       SCAL2
         11         11
-1.0    +16        1.0         0.0         1.0
         12         12
-1.0    +16        1.0         0.0         1.0
         13         13
-1.0    +16        1.0         0.0         1.0
         14         14
-1.0    +16        1.0         0.0         1.0
         15         15
-1.0    +16        1.0         0.0         1.0
         16         16
-1.0    +16        1.0         0.0         1.0
         17         17
-1.0    +16        1.0         0.0         1.0
         18         18
-1.0    +16        1.0         0.0         1.0
         19         19
-1.0    +16        1.0         0.0         1.0
         20         20
-1.0    +16        1.0         0.0         1.0
```

```
           21          21
-1.0     +16         1.0          0.0          1.0
           22          22
-1.0     +16         1.0          C.0          1.0
$V
END
```

APPENDIX E

COPES OUTPUT--DESIGN CASE NO. 1

```
CCCCCCC   CCOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                   IMAGE

  1)  $A  TITLE
  2)     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)  $E    NCALC         NCV         NSV       N2VAR     NXAPRX     IPNPLT     IPDBG
  4)            2           2                                          0
  5)  $C   IPRINT       ITMAX      ICNDIR       NSCAL      ITRM     LINOBJ     NACMX1
  6)            1        1000                      -1                            15
  7)  $C1    FDCH       FDCHM          CT       CTMIN       CTL     CTLMIN      THETA
  8)       0.0001      0.0001
  9)  $C2  DELFUN      DABFUN      ALPHAX      ABOBJ1
 10)
 10)
 11)  $E   NCVTOT        IOBJ      SGNOPT
 12)            2           1         1.0
 13)  $F      VLB         VUB           X        SCAL
 14)         0.01         1.8         0.1         1.0
 15)          0.4         1.4         0.5         1.0
 16)  $C   NCSSGN       IDSGN       AMULT
 17)            1          23         1.0
 18)            2           7         1.0
 19)  $F    NCONS
 20)            9
 21)  $I1    ICON        JCON        LCON
 22)  $I2      BL       SCAL1          BU       SCAL2
 23)           11          11
 24)  -1.0    +16         1.0         0.0         1.0
 25)           12          12
 26)  -1.0    +16         1.0         0.0         1.0
 27)           13          13
 28)  -1.0    +16         1.0         0.0         1.0
 29)           14          14
 30)  -1.0    +16         1.0         0.0         1.0
 31)           15          15
 32)  -1.0    +16         1.0         0.0         1.0
 33)           16          16
 34)  -1.0    +16         1.0         0.0         1.0
 35)           17          17
 36)  -1.0    +16         1.0         0.0         1.0
 37)           18          18
 38)  -1.0    +16         1.0         0.0         1.0
 39)           19          19
 40)  -1.0    +16         1.0         0.0         1.0
 41)  IN
 42)  END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CONTROL PARAMETERS:
CALCULATION CONTROL,                          NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,              NDV =    2
NUMBER OF SENSITIVITY VARIABLES,                NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,             N2VAR =    0
NUMBER OF APPROXIMATING VAR.                 NXAPRX =    0
INPUT INFORMATION PRINT CODE,                IPNPUT =    0
DEBUG PRINT CODE,                             IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                  =    1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)         =  0.10000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX   ICNDIR   NSCAL    ITRM    LINOBJ  NACMX1   NFDG
  1     1000      0       -1        0        0      15        0

FDCH            FDCHM            CT              CTMIN
0.10000E-03     0.10000E-03      0.0             0.0

CTL             CTLMIN           THETA           PHI
0.0             0.0              0.0             0.0

DELFUN          DABFUN           ALPHAX          ABOBJ1
0.0             0.0              0.0             0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER          UPPER          INITIAL
NO.        BOUND          BOUND          VALUE           SCALE
  1      0.10000E-01    0.18000E+01    0.10000E+00    0.10000E+01
  2      0.40000E+00    0.14000E+01    0.50000E+00    0.10000E+01

DESIGN VARIABLES
       D. V.     GLOBAL     MULTIPLYING
ID     NO.      VAR. NO.    FACTOR
 1      1         23       0.10000E+01
 2      2          7       0.10000E+01

CONSTRAINT INFORMATION

THERE ARE  9 CONSTRAINT SETS
       GLOBAL   GLOBAL   LINEAR
 ID    VAR. 1   VAR. 2     ID        LOWER        NORMALIZATION     UPPER       NORMALIZATION
                                     BOUND          FACTOR          BOUND          FACTOR
  1      11       11        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  2      12       12        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  3      13       13        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  4      14       14        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  5      15       15        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  6      16       16        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  7      17       17        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  8      18       18        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01
  9      19       19        0    -0.11000E+16    0.10000E+01      0.0         0.10000E+01

TOTAL NUMBER OF CONSTRAINED PARAMETERS =    9


* * ESTIMATED DATA STORAGE REQUIREMENTS
```

```
  57         450      10000           50          57        1000

OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRCNA"

DESIGN VARIABLES SPECIFIED:  PE,V,AEDVAO,DIA,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =   55.0000
                             DENSITY (LBF-SEC2/FT4)                =    1.9384
                             VISCOSITY (FT2/SEC)                   = 0.122649997E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =   14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =    0.2470

HULL PARAMETERS:             WAKE FRACTION                         =    0.2200
                             THRUST DEDUCTION FRACTION             =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =    1.0250
                             NUMBER OF PROPELLERS                  =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =   15.0000
                             DIAMETER LIMIT (FT)                   =   22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =       5.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =    5400.0

SELECTION VALUES:            PE  (HP)                              =   18153.0
                             V   (FT/SEC)                          =   40.5120
                             N   (RPM)                             =  861.8003
                             QS  (FT-LBF)                          =  29533744.0
                             PD  (HP)                              =4846085.00

                             J                                     =    0.1000
                             KT                                    =    0.1735
                             KQ                                    =    0.0143
                             ETAC                                  =    0.1527
                             REY75R                                =   0.5E+09
                             DIA (FT)                              =   22.0000
                             P/D                                   =    0.5000
                             AE/AO                                 =    0.8500
                             T/C .75R                              =    0.0348

CONSTRAINT VALUES:           MAX DIA (FT)                          =   22.0000
                             MIN AE/AO                             =   28.7882
                             MIN T/C .75R                          =  0.019990
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*                   C O N M I N                     *
*               FORTRAN PROGRAM FOR                 *
*        CONSTRAINED FUNCTION MINIMIZATION          *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.152694E+00

DECISION VARIABLES (X-VECTOR)
  1)     0.10000E+00  0.50000E+00

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.62500E-01 -0.93750E+00 -0.23415E+03 -0.76485E+03 -0.40000E+00 -0.20000E+00
  7)    -0.20691E-01 -0.22788E+00 -0.53755E+02
```

```
FINAL OPTIMIZATION INFORMATION

OBJ =  -0.709073E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.73712E+00  0.10036E+01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.46070E+00 -0.53930E+00 -0.32395E+02 -0.96660E+03 -0.40000E+00 -0.20000E+00
  7)    -0.20691E-01 -0.22788E+00  0.12279E-04

THERE ARE    1 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
    5

THERE ARE    0 VIOLATED CONSTRAINTS

THERE ARE    0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION
     ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR  3 ITERATIONS
     ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR  3 ITERATIONS

NUMBER OF ITERATIONS =   14

OBJECTIVE FUNCTION WAS EVALUATED          69  TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED       69  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.70907E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	23	0.10000E-01	0.73712E+00	0.18000E+01
2	2	7	0.40000E+00	0.10036E+01	0.14000E+01

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.46070E+00	0.0
2	12	-0.11000E+16	-0.53930E+00	0.0
3	13	-0.11000E+16	-0.32395E+02	0.0
4	14	-0.11000E+16	-0.56660E+03	0.0
5	15	-0.11000E+16	-0.40000E+00	0.0
6	16	-0.11000E+16	-0.20000E+00	0.0
7	17	-0.11000E+16	-0.20651E-01	0.0
8	18	-0.11000E+16	-0.22788E+00	0.0
9	19	-0.11000E+16	0.12279E-04	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRCNA"

DESIGN VARIABLES SPECIFIED:  PE,V,AE/AC,DIA,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                         =   55.0000
                             DENSITY (LBF-SEC2/FT4)               =    1.9384
                             VISCOSITY (FT2/SEC)                  = 0.122849997E-04
                             ATMOSPHERIC PRESSURE (PSIA)          =   14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)   =    0.2470

HULL PARAMETERS:             WAKE FRACTION                        =    0.2200
                             THRUST DEDUCTION FRACTION            =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY         =    1.0250
                             NUMBER OF PROPELLERS                 =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)       =   15.0000
                             DIAMETER LIMIT (FT)                  =   22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                     =       5.0
                             MATERIAL TYPE                        =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)               =    5400.0

SELECTION VALUES:            PE  (HP)                             =   16153.0
                             V   (FT/SEC)                         =   40.5120
                             N   (RPM)                            =  116.9142
                             QS  (FT-LBF)                         =  1080451.0
                             PD  (HP)                             =  24051.27

                             J                                    =    0.7371
                             KT                                   =    0.1722
                             KQ                                   =    0.0285
                             ETAO                                 =    0.7091
                             REY75R                               =   0.7E+08
                             DIA (FT)                             =   22.0000
                             P/D                                  =    1.0036
                             AE/AO                                =    0.8500
                             T/C .75R                             =    0.0348

CONSTRAINT VALUES:           MAX DIA (FT)                         =   22.0000
                             MIN AE/AO                            =    0.5258
                             MIN T/C .75R                         =  0.021266
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	70
3	2

COPES

CONTROL PROGRAM
FOR
ENGINEERING SYNTHESIS

TITLE
WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                        IMAGE

  1)   $A  TITLE
  2)     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)   $B    NCALC         NDV          NSV        N2VAR     NXAPRX     IPNPLT      IPDBG
  4)             2           2                                             0
  5)   $C   IPRINT       ITMAX       ICNDIR        NSCAL       ITRM     LINOBJ     NACMX1
  6)             1        1000                        -1                             15
  7)   $C1    FDCH        FDCHM          CT        CTMIN        CTL     CTLMIN      THETA
  8)        0.0001      0.0001
  9)   $C2  DELFUN       DABFUN      ALPHAX       ABOBJ1
 10)
 10)
 11)   $E   NDVTOT         IOBJ      SGNOPT
 12)             2            1         1.0
 13)   $F      VLB          VUB           X         SCAL
 14)          0.01          1.8         0.1          1.0
 15)           0.4          1.4         0.5          1.0
 16)   $G   NCSSGN        IDSGN       AMULT
 17)             1           23         1.0
 18)             2            7         1.0
 19)   $H    NCONS
 20)             9
 21)   $I1    ICON         JCON        LCON
 22)   $I2      BL        SCAL1          BU        SCAL2
 23)            11           11
 24)   -1.0    +16          1.0         0.0          1.0
 25)            12           12
 26)   -1.0    +16          1.0         0.0          1.0
 27)            13           13
 28)   -1.0    +16          1.0         0.0          1.0
 29)            14           14
 30)   -1.0    +16          1.0         0.0          1.0
 31)            15           15
 32)   -1.0    +16          1.0         0.0          1.0
 33)            16           16
 34)   -1.0    +16          1.0         0.0          1.0
 35)            17           17
 36)   -1.0    +16          1.0         0.0          1.0
 37)            18           18
 38)   -1.0    +16          1.0         0.0          1.0
 39)            19           19
 40)   -1.0    +16          1.0         0.0          1.0
 41)   $N
 42)   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                          NCALC  =    2
NUMBER OF GLOBAL DESIGN VARIABLES,              NDV  =    2
NUMBER OF SENSITIVITY VARIABLES,                NSV  =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,             N2VAR  =    0
NUMBER OF APPROXIMATING VAR.                 NXAPRX  =    0
INPUT INFORMATION PRINT CODE,                IPNPUT  =    0
DEBUG PRINT CODE,                             IPDBG  =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE               =    1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) =  0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT   ITMAX   ICNDIR   NSCAL   ITRM   LINOBJ   NACMX1   NFDG
  1      1000      0       -1       0       0       15        0

 FDCH             FDCHM            CT               CTMIN
 0.10000E-02      0.10000E-03      0.0              0.0

 CTL              CTLMIN           THETA            PHI
 0.0              0.0              0.0              0.0

 DELFUN           DABFUN           ALPHAX           ABOBJ1
 0.0              0.0              0.0              0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER           UPPER           INITIAL
NO.        BOUND           BOUND           VALUE            SCALE
  1     0.10000E-01     0.18000E+01     0.10000E+00     0.10000E+01
  2     0.40000E+00     0.14000E+01     0.50000E+00     0.10000E+01

DESIGN VARIABLES
        D. V.      GLOBAL      MULTIPLYING
ID       NO.      VAR. NO.       FACTOR
 1        1          23        0.10000E+01
 2        2           7        0.10000E+01

CONSTRAINT INFORMATION

THERE ARE   9 CONSTRAINT SETS
        GLOBAL  GLOBAL   LINEAR      LOWER        NORMALIZATION      UPPER        NORMALIZATION
 ID     VAR. 1  VAR. 2     ID        BOUND           FACTOR          BOUND           FACTOR
  1       11      11       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  2       12      12       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  3       13      13       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  4       14      14       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  5       15      15       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  6       16      16       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  7       17      17       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  8       18      18       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
  9       19      19       0     -0.10000E+16    0.10000E+01      0.0          0.10000E+01
TOTAL NUMBER OF CONSTRAINED PARAMETERS =    9


* * ESTIMATED DATA STORAGE REQUIREMENTS
```

```
      57        450     10000          30         94       1000

CPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRCNK"

DESIGN VARIABLES SPECIFIED:  PE,V,AECVAC,DIA,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =    55.0000
                             DENSITY (LBF-SEC2/FT4)                =     1.9384
                             VISCOSITY (FT2/SEC)                   = 0.122849997E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =    14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =     0.2470

HULL PARAMETERS:             WAKE FRACTION                         =     0.2200
                             THRUST DEDUCTION FRACTION             =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =     1.0250
                             NUMBER OF PROPELLERS                  =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =    15.0000
                             DIAMETER LIMIT (FT)                   =    22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =        5.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =     5400.0

SELECTION VALUES:            PE  (HP)                              =    16153.0
                             V   (FT/SEC)                          =    40.5120
                             N   (RPM)                             =   861.8003
                             QS  (FT-LBF)                          =  29533744.0
                             PD  (HP)                              =4846085.00

                             J                                     =     0.1000
                             KT                                    =     0.1735
                             KQ                                    =     0.0143
                             ETAC                                  =     0.1927
                             REY75R                                =    0.5E+09
                             DIA (FT)                              =    22.0000
                             P/D                                   =     0.5000
                             AE/AC                                 =     0.8500
                             T/C .75R                              =     0.0348

CONSTRAINT VALUES:           MAX DIA (FT)                          =    22.0000
                             MIN AE/AO                             =    26.7882
                             MIN T/C .75R                          =   0.134760
```

```
* * * * * * * * * * * * * * * * * * * * * * * * *
*                                               *
*                  C C N M I N                  *
*               FORTRAN PROGRAM FOR             *
*        CONSTRAINEC FUNCTION MINIMIZATION      *
*                                               *
* * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATICN

OBJ =  -C.152694E+0C

DECISICN VARIABLES (X-VECTOR)
  1)    C.10000E+00  C.500CCE+00

CONSTRAINT VALUES (G-VECTOR)
  1)   -C.62500E-01 -0.9375CE+C0 -0.23415E+C3 -0.76485E+03 -C.40000E+00 -0.20000E+00
  7)   -0.2C691E-01 -0.22788E+00 -0.53755E+C2
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =  -0.709073E+00

 DECISION VARIABLES (X-VECTOR)
   1)    0.73712E+00  0.10036E+01

 CONSTRAINT VALUES (G-VECTOR)
   1)   -0.46070E+00 -0.53930E+00 -0.32355E+02 -0.96660E+03 -0.40000E+00 -0.20000E+00
   7)   -0.20691E-01 -0.22788E+00  0.12279E-04

 THERE ARE    1 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     9

 THERE ARE    0 VIOLATED CONSTRAINTS

 THERE ARE    0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR  3 ITERATIONS
      ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR  3 ITERATIONS

 NUMBER OF ITERATIONS =   14

 OBJECTIVE FUNCTION WAS EVALUATED         69  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED      69  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.70907E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	23	0.10000E-01	0.73712E+00	0.10000E+01
2	2	7	0.40000E+00	0.10036E+01	0.14000E+01

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.46070E+00	0.0
2	12	-0.11000E+16	-0.53930E+00	0.0
3	13	-0.11000E+16	-0.32395E+02	0.0
4	14	-0.11000E+16	-0.56660E+03	0.0
5	15	-0.11000E+16	-0.40000E+00	0.0
6	16	-0.11000E+16	-0.20000E+00	0.0
7	17	-0.11000E+16	-0.20651E-01	0.0
8	18	-0.11000E+16	-0.22788E+00	0.0
9	19	-0.11000E+16	0.12279E-04	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:  PE,V,AEOVAO,DIA,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =    55.0000
                             DENSITY (LBF-SEC2/FT4)                =     1.9384
                             VISCOSITY (FT2/SEC)                   = 0.122849997E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =    14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =     0.2470

HULL PARAMETERS:             WAKE FRACTION                         =     0.2200
                             THRUST DEDUCTION FRACTION             =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =     1.0250
                             NUMBER OF PROPELLERS                  =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =    15.0000
                             DIAMETER LIMIT (FT)                   =    22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =        5.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =     5400.0

SELECTION VALUES:            PE (EHP)                              =    16153.0
                             V  (FT/SEC)                           =    40.5120
                             N  (RPM)                              =   116.9142
                             QS (FT-LBF)                           =   1080451.0
                             PD  (HP)                              =   24051.27

                             J                                     =     0.7371
                             KT                                    =     0.1722
                             KQ                                    =     0.0285
                             ETAO                                  =     0.7091
                             REY75R                                =    0.7E+08
                             DIA (FT)                              =    22.0000
                             P/D                                   =     1.0036
                             AE/AO                                 =     0.8500
                             T/C .75R                              =     0.0348

CONSTRAINT VALUES:           MAX DIA (FT)                          =    22.0000
                             MIN AE/AO                             =     0.5258
                             MIN T/C .75R                          =   0.050761
```

```
PROGRAM CALLS TO ANALIZ

    ICALL    CALLS
      1        1
      2       70
      3        2
```

```
CCCCCCC   OOOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                    IMAGE

  1)   $A  TITLE
  2)     WAGENINGEN  B-SERIES  PROPELLER  OPTIMIZATION
  3)   $E    NCALC        NCV        NSV      N2VAR     NXAPRX     IPNPLT     IPDBG
  4)             2          5                                         0
  5)   $C   IFRINT      ITMAX     ICNDIR      NSCAL       ITRM     LINDEJ     NALMX1
  6)             1       1000                   -1         30                   15
  7)   $C1    FDCH      FDCFN         CT      CTMIN        CTL     CTLMIN      THETA
  8)       0.0001     0.0001
  9)   $C2  DELFUN     DABFUN     ALFMAX     ABOBJ1
 10)
 10)
 11)   $E   NCVTOT       ICBJ     SGNOPT
 12)             5          1        1.0
 13)   $F      VLB        VUB          X       SCAL
 14)           0.2        1.1       0.30        1.0
 15)           1.0       50.0       20.0       10.0
 16)          0.01        1.6        0.1        1.0
 17)           0.4        1.4        0.5        1.0
 18)         0.003        0.5     0.0300      0.010
 19)   $G   NCSSGN      IDSGN      AMULT
 20)             1          3        1.0
 21)             2          4        1.0
 22)             3         23        1.0
 23)             4          7        1.0
 24)             5          9        1.0
 25)   $H    NCONS
 26)            12
 27)   $I1    ICON       JCON       LCON
 28)   $I2      BL      SCAL1         BU      SCAL2
 29)            11         11
 30)   -1.0    +16        1.0        0.0        1.0
 31)            12         12
 32)   -1.0    +16        1.0        0.0        1.0
 33)            13         13
 34)   -1.0    +16        1.0        0.0        1.0
 35)            14         14
 36)   -1.0    +16        1.0        0.0        1.0
 37)            15         15
 38)   -1.0    +16        1.0        0.0        1.0
 39)            16         16
 40)   -1.0    +16        1.0        0.0        1.0
 41)            17         17
 42)   -1.0    +16        1.0        0.0        1.0
 43)            18         18
 44)   -1.0    +16        1.0        0.0        1.0
 45)            19         19
 46)   -1.0    +16        1.0        0.0        1.0
 47)            20         20
 48)   -1.0    +16        1.0        0.0        1.0
 49)            21         21
 50)   -1.0    +16        1.0        0.0        1.0
 51)            22         22
 52)   -1.0    +16        1.0        0.0        1.0
 53)   $N
 54)   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CONTROL PARAMETERS:
CALCULATION CONTROL,                      NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,          NDV =    5
NUMBER OF SENSITIVITY VARIABLES,            NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,         N2VAR =    0
NUMBER OF APPROXIMATING VAR.,            NXAPRX =    0
INPUT INFORMATION PRINT CODE,            IPNPUT =    0
DEBUG PRINT CODE,                         IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE            =    1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) =  0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX    ICNDIR    NSCAL    ITRM    LINOBJ  NACMX1   NFDG
  1     1000       0        -1      30        0      15        0

FDCH              FDCHM             CT                CTMIN
0.10000E-03       0.10000E-03       0.0               0.0

CTL               CTLMIN            THETA             PHI
0.0               0.0               0.0               0.0

DELFUN            DABFUN            ALPHAX            ABOBJ1
0.0               0.0               0.0               0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER           UPPER           INITIAL
NO.        BOUND           BOUND           VALUE            SCALE
  1     0.20000E+00     0.11000E+01     0.30000E+00     0.10000E+01
  2     0.10000E+01     0.50000E+02     0.30000E+02     0.10000E+02
  3     0.0             0.10000E+08     0.10000E+00     0.10000E+01
  4     0.40000E+00     0.14000E+01     0.53000E+00     0.10000E+01
  5     0.30000E-02     0.50000E+00     0.30000E-01     0.10000E-01

DESIGN VARIABLES
      D. V.      GLOBAL      MULTIPLYING
ID    NO.      VAR. NO.       FACTOR
 1     1           3        0.10000E+01
 2     2           4        0.10000E+01
 3     3          23        0.10000E+01
 4     4           7        0.10000E+01
 5     5           5        0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
      GLOBAL   GLOBAL   LINEAR      LOWER         NORMALIZATION      UPPER          NORMALIZATION
ID    VAR. 1   VAR. 2     ID        BOUND           FACTOR           BOUND             FACTOR
 1     11       11        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 2     12       12        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 3     13       13        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 4     14       14        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 5     15       15        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 6     16       16        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 7     17       17        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 8     18       18        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
 9     19       19        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
10     20       20        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
11     21       21        0     -0.11000E+16     0.10000E+01      0.0             0.10000E+01
```

```
TOTAL NUMBER OF CONSTRAINED PARAMETERS =    12


* * ESTIMATED DATA STORAGE REQUIREMENTS
                REAL                                  INTEGER
INPUT   EXECUTION   AVAILABLE        INPUT   EXECUTION   AVAILABLE
  87        570       10000            57        124        1000
```

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRCNA"

DESIGN VARIABLES SPECIFIED:  PE,V

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                              =   55.0000
                             DENSITY (LBF-SEC2/FT4)                    =    1.9384
                             VISCOSITY (FT2/SEC)                       = 0.122849997E-04
                             ATMOSPHERIC PRESSURE (PSIA)               =   14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)        =    0.2470

HULL PARAMETERS:             WAKE FRACTION                             =    0.2200
                             THRUST DEDUCTION FRACTION                 =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY              =    1.0250
                             NUMBER OF PROPELLERS                      =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)            =   15.0000
                             DIAMETER LIMIT (FT)                       =   22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                          =       5.0
                             MATERIAL TYPE                             =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                    =    5400.0

SELECTION VALUES:            PE  (HP)                                  =   16153.0
                             V   (FT/SEC)                              =   40.5120
                             N   (RPM)                                 =  631.9868
                             QS  (FT-LBF)                              =  83126272.0
                             PD  (HP)                                  =***********

                             J                                         =    0.1000
                             KT                                        =    0.1879
                             KQ                                        =    0.0160
                             ETAO                                      =    0.1865
                             REY75R                                    =  0.7E+09
                             DIA (FT)                                  =   30.0000
                             P/D                                       =    0.5000
                             AE/AO                                     =    0.3000
                             T/C .75R                                  =    0.0300

CONSTRAINT VALUES:           MAX DIA (FT)                              =   22.0000
                             MIN AE/AO                                 =   31.1615
                             MIN T/C .75R                              =  0.057932
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*                  C O N M I N                      *
*                                                   *
*             FORTRAN PROGRAM FOR                   *
*                                                   *
*       CONSTRAINED FUNCTION MINIMIZATION           *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.166489E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.30000E+00  0.30000E+02  0.10000E+00  0.50000E+00  0.30000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.62500E-01 -0.93750E+00 -0.33074E+03 -0.66826E+03  0.15000E+00 -0.75000E+00
  7)   -0.15930E-01 -0.23264E+00 -0.10917E+03  0.36364E+00  0.10287E+03  0.93106E+00
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =  -0.710857E+00

 DECISION VARIABLES (X-VECTOR)
   1)    0.62049E+00  0.21999E+02  0.73433E+00  0.99813E+00  0.33004E-01

 CONSTRAINT VALUES (G-VECTOR)
   1)   -0.45895E+00 -0.54105E+00 -0.38016E+02 -0.96096E+03 -0.37049E+00 -0.22951E+00
   7)   -0.18935E-01 -0.22963E+00 -0.16354E-02 -0.31233E-04 -0.35786E+00 -0.33350E+00

 THERE ARE    2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     5   10

 THERE ARE    0 VIOLATED CONSTRAINTS

 THERE ARE    0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

 NUMBER OF ITERATIONS =   83

 OBJECTIVE FUNCTION WAS EVALUATED         548  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED      548  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.71086E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.20000E+00	0.82049E+00	0.11000E+01
2	2	4	0.10000E+01	0.21999E+02	0.50000E+02
3	3	23	0.0	0.73433E+00	0.10000E+08
4	4	7	0.40000E+00	0.99813E+00	0.14000E+01
5	5	9	0.30000E-02	0.33004E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.45895E+00	0.0
2	12	-0.11000E+16	-0.54105E+00	0.0
3	13	-0.11000E+16	-0.38016E+02	0.0
4	14	-0.11000E+16	-0.56098E+03	0.0
5	15	-0.11000E+16	-0.37045E+00	0.0
6	16	-0.11000E+16	-0.22951E+00	0.0
7	17	-0.11000E+16	-0.18934E-01	0.0
8	18	-0.11000E+16	-0.22963E+00	0.0
9	19	-0.11000E+16	-0.16251E-02	0.0
10	20	-0.11000E+16	-0.40948E-04	0.0
11	21	-0.11000E+16	-0.35786E+00	0.0
12	22	-0.11000E+16	-0.33345E+00	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRCNA"

DESIGN VARIABLES SPECIFIED:  PE,V

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =   55.0000
                             DENSITY (LBF-SEC2/FT4)                =    1.9384
                             VISCOSITY (FT2/SEC)                   = 0.12849997E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =   14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =    0.2470

HULL PARAMETERS:             WAKE FRACTION                         =    0.2200
                             THRUST DEDUCTION FRACTION             =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =    1.0250
                             NUMBER OF PROPELLERS                  =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =   15.0000
                             DIAMETER LIMIT (FT)                   =   22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =       5.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =    5400.0

SELECTION VALUES:            PE  (HP)                              =   18153.0
                             V   (FT/SEC)                          =   40.5120
                             N   (RPM)                             =  117.3644
                             QS  (FT-LBF)                          =  1075368.0
                             PD   (HP)                             =  24030.30

                             J                                     =    0.7343
                             KT                                    =    0.1713
                             KQ                                    =    0.0282
                             ETAC                                  =    0.7109
                             REY75R                                =  0.8E+08
                             DIA (FT)                              =   21.9991
                             P/D                                   =    0.9981
                             AE/AO                                 =    0.8205
                             T/C .75R                              =    0.0330

CONSTRAINT VALUES:           MAX DIA (FT)                          =   22.0000
                             MIN AE/AO                             =    0.5269
                             MIN T/C .75R                          =  0.021998
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	549
3	2

```
CCCCCCC   OCOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

```
CARD IMAGES OF CONTROL DATA

CARD                      IMAGE

 1)  $A  TITLE
 2)    WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
 3)  $B    NCALC        NDV        NSV      N2VAR     NXAPRX     IPNPLT     IPDBG
 4)            2          5                                       0
 5)  $C   IPRINT      ITMAX     ICNDIR     NSCAL       ITRM     LINOBJ     NACMX1
 6)            1       1000                   -1         30                  15
 7)  $C1    FDCH      FDCHM         CT      CTMIN        CTL     CTLMIN      THETA
 8)       0.0001     0.0001
 9)  $C2  DELFUN     DABFUN     ALPHAX     ABOBJ1
10)
10)
11)  $E   NDVTOT       IOBJ     SGNOPT
12)            5          1        1.0
13)  $F      VLB        VUB          X       SCAL
14)          0.2        1.1       0.30        1.0
15)          1.0       50.0       30.0       10.0
16)         0.01        1.6        0.1        1.0
17)          0.4        1.4        0.5        1.0
18)        0.003        0.5     0.0300      0.010
19)  $G   NESSGN      IDSGN      AMULT
20)            1          3        1.0
21)            2          4        1.0
22)            3         23        1.0
23)            4          7        1.0
24)            5          9        1.0
25)  $H    NCONS
26)           12
27)  $I1    ICON       JCON       LCON
28)  $I2      BL      SCAL1         BU      SCAL2
29)           11         11
30)  -1.0    +16        1.0        0.0        1.0
31)           12         12
32)  -1.0    +16        1.0        0.0        1.0
33)           13         13
34)  -1.0    +16        1.0        0.0        1.0
35)           14         14
36)  -1.0    +16        1.0        0.0        1.0
37)           15         15
38)  -1.0    +16        1.0        0.0        1.0
39)           16         16
40)  -1.0    +16        1.0        0.0        1.0
41)           17         17
42)  -1.0    +16        1.0        0.0        1.0
43)           18         18
44)  -1.0    +16        1.0        0.0        1.0
45)           19         19
46)  -1.0    +16        1.0        0.0        1.0
47)           20         20
48)  -1.0    +16        1.0        0.0        1.0
49)           21         21
50)  -1.0    +16        1.0        0.0        1.0
51)           22         22
52)  -1.0    +16        1.0        0.0        1.0
53)  $N
54)  END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                        NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,            NDV =    5
NUMBER OF SENSITIVITY VARIABLES,              NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,           N2VAR =    0
NUMBER OF APPROXIMATING VAR.               NXAPRX =    0
INPUT INFORMATION PRINT CODE,              IPNPUT =    0
DEBUG PRINT CODE,                           IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                  =  1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)  =  0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT   ITMAX    ICNDIR   NSCAL    ITRM    LINOBJ  NACMX1   NFDG
  1      1000       0       -1       30       0      15       0

 FDCH             FDCHM              CT                CTMIN
 0.10000E-03      0.10000E-03        0.0               0.0

 CTL              CTLMIN             THETA             PHI
 0.0              0.0                0.0               0.0

 DELFUN           DABFUN             ALPHAX            ABOBJ1
 0.0              0.0                0.0               0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER            UPPER           INITIAL
NO.        BOUND            BOUND           VALUE            SCALE
  1      -0.20000E+00     0.11000E+01     0.30000E+00     0.10000E+01
  2       0.10000E+01     0.30000E+01     0.30000E+01     0.10000E+01
  3       0.0             0.10000E+01     0.10000E+00     0.10000E+01
  4       0.40000E+00     0.14000E+01     0.50000E+00     0.10000E+01
  5       0.30000E-02     0.50000E+00     0.30000E-01     0.10000E-01


DESIGN VARIABLES
       D. V.       GLOBAL      MULTIPLYING
ID      NO.       VAR. NO.       FACTOR
 1       1            3        0.1000E+01
 2       2            4        0.1000E+01
 3       3           23        0.1000E+01
 4       4            7        0.1000E+01
 5       5            9        0.1000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
        GLOBAL   GLOBAL   LINEAR       LOWER       NORMALIZATION      UPPER      NORMALIZATION
 ID     VAR. 1   VAR. 2     ID         BOUND          FACTOR          BOUND         FACTOR
  1       11       11       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  2       12       12       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  3       13       13       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  4       14       14       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  5       15       15       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  6       16       16       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  7       17       17       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  8       18       18       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
  9       19       19       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
 10       20       20       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
 11       21       21       0      -0.1000E+16     0.10000E+01      0.0         0.10000E+01
```

```
TOTAL NUMBER OF CONSTRAINED PARAMETERS =    12


* * ESTIMATED DATA STORAGE REQUIREMENTS

           REAL                               INTEGER
INPUT   EXECUTION   AVAILABLE        INPUT   EXECUTION   AVAILABLE
  87       570        10000            57       124        1000
```

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 1
                             SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:  PE,V

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =    59.0000
                             DENSITY (LBF-SEC2/FT4)                =     1.9384
                             VISCOSITY (FT2/SEC)                   = 0.12284999 7E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =    14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =     0.2470

HULL PARAMETERS:             WAKE FRACTION                         =     0.2200
                             THRUST DEDUCTION FRACTION             =     0.1500
                             RELATIVE ROTATIVE EFFICIENCY          =     1.0250
                             NUMBER OF PROPELLERS                  =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =    15.0000
                             DIAMETER LIMIT (FT)                   =    22.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =        5.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =     5400.0

SELECTION VALUES:            PE (HP)                               =    16155.0
                             V  (FT/SEC)                           =    40.5120
                             N  (RPM)                              =   631.9868
                             QS (FT-LBF)                           =  83126272.0
                             PD  (HP)                              =**********

                             J                                     =     0.1000
                             KT                                    =     0.1879
                             KQ                                    =     0.0160
                             ETAO                                  =     0.1865
                             REY75R                                =    0.7E+09
                             DIA (FT)                              =    30.0000
                             P/D                                   =     0.5000
                             AE/AO                                 =     0.3000
                             T/C .75R                              =     0.0300

CONSTRAINT VALUES:           MAX DIA (FT)                          =    22.0000
                             MIN AE/AO                             =    31.1615
                             MIN T/C .75R                          =   0.198487
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                 *
*                  C O N M I N                    *
*              FORTRAN PROGRAM FOR                *
*        CONSTRAINED FUNCTION MINIMIZATION        *
*                                                 *
* * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.166489E+00

DECISION VARIABLES (X-VECTOR)
  1)     0.30000E+00  0.30000E+02  0.10000E+00  0.50000E+00  0.30000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.62500E-01 -0.93750E+00 -0.33074E+03 -0.66826E+03  0.15000E+00 -0.75000E+00
  7)    -0.15930E-01 -0.23264E+00 -0.10917E+03  0.36364E+00  0.10287E+03  0.56162E+01
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =  -0.70657SE+00

 DECISION VARIABLES (X-VECTOR)
   1)    0.81488E+00  0.21966E+02  0.73936E+00  0.10071E+01  0.64152E-01

 CONSTRAINT VALUES (G-VECTOR)
   1)   -0.44210E+00 -0.53759E+00 -0.25386E+02 -0.97361E+03 -0.36488E+00 -0.23512E+00
   7)   -0.50082E-01 -0.19848E+00  0.17331E-02 -0.15509E-02 -0.35365E+00 -0.16980E+00

 THERE ARE    2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     9   10

 THERE ARE    0 VIOLATED CONSTRAINTS

 THERE ARE    0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR 30 ITERATIONS
      ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

 NUMBER OF ITERATIONS =   73

 OBJECTIVE FUNCTION WAS EVALUATED          491  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED       491  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.70658E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.20000E+00	0.81488E+00	0.11000E+01
2	2	4	0.10000E+01	0.21966E+02	0.50000E+02
3	3	23	0.0	0.73936E+00	0.10000E+08
4	4	7	0.40000E+00	0.10071E+01	0.14000E+01
5	5	9	0.30000E-02	0.64152E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.46210E+00	0.0
2	12	-0.11000E+16	-0.53790E+00	0.0
3	13	-0.11000E+16	-0.25388E+02	0.0
4	14	-0.11000E+16	-0.97361E+03	0.0
5	15	-0.11000E+16	-0.36488E+00	0.0
6	16	-0.11000E+16	-0.23512E+00	0.0
7	17	-0.11000E+16	-0.50082E-01	0.0
8	18	-0.11000E+16	-0.15848E+00	0.0
9	19	-0.11000E+16	0.17331E-02	0.0
10	20	-0.11000E+16	-0.15509E-02	0.0
11	21	-0.11000E+16	-0.35365E+00	0.0
12	22	-0.11000E+16	-0.16980E+00	0.0

```
OPTIMIZATION RESULTS -------  DESIGN CASE NO. 1
                              SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:   PE,V

ENVIRONMENTAL PARAMETERS:     TEMP (DEG F)                          =   55.0000
                              DENSITY (LBF-SEC2/FT4)                =    1.9384
                              VISCOSITY (FT2/SEC)                   = 0.122849997E-04
                              ATMOSPHERIC PRESSURE (PSIA)           =   14.7000
                              WATER VAPORIZATION PRESSURE (PSIA)    =    0.2470

HULL PARAMETERS:              WAKE FRACTION                         =    0.2200
                              THRUST DEDUCTION FRACTION             =    0.1900
                              RELATIVE ROTATIVE EFFICIENCY          =    1.0250
                              NUMBER OF PROPELLERS                  =       1.0
                              DEPTH TO SHAFT CENTERLINE (FT)        =   15.0000
                              DIAMETER LIMIT (FT)                   =   22.0000

PROPELLER PARAMETERS:         NUMBER OF BLADES                      =       5.0
                              MATERIAL TYPE                         = STAINLESS STEEL
                              ALLOWABLE STRESS (PSI)                =    5400.0

SELECTION VALUES:             PE (HP)                               =   18153.0
                              V  (FT/SEC)                           =   40.5120
                              N  (RPM)                              =  116.7419
                              QS (FT-LBF)                           = 1084003.0
                              PD (HP)                               =  24094.79

                              J                                     =    0.7394
                              KT                                    =    0.1736
                              KQ                                    =    0.0289
                              ETAO                                  =    0.7066
                              REY75R                                =  0.5E+08
                              DIA (FT)                              =   21.9659
                              P/D                                   =    1.0071
                              AE/AO                                 =    0.8149
                              T/C .75R                              =    0.0642

CONSTRAINT VALUES:            MAX DIA (FT)                          =   22.0000
                              MIN AE/AO                             =    0.5267
                              MIN T/C .75R                          =  0.053259
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	452
3	2

APPENDIX F

ANALIZ CODES--DESIGN CASE NO. 2

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD,VAK
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 2" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=64.4
           WATRO=1.9892
           WATNU=.00001190O
           PATM=14.697
           PWATVA=.295439291
CC
CC         PROPELLER PARAMETERS
CC
           Z=6.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TD=0.19
           ETARR=1.025
           NOSCRW=1.0
           HCL=21.9827
           DIALIM=30.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
CC
```

```
      QS=1210129.835
      N=110.0
      VK=20.0641025 6
      V=1.688*VK
CC
CC    END OF INPUT-INITIALIZATION PHASE
CC
      GO TO 3
C
C     EXECUTION PHASE
C
    1 CONTINUE
      IF(.NOT.(ICALC.EQ.2))GO TO 2
         TC75R=((0.0185-0.00125*Z)*Z)/(2.073*AEDVAO)
         CALL RCCAL(DIA)
         CALL CH75RA(C75R)
         CALL REY75R(C75R,R75R)
         CALL COEFSA(RJ,R75R,KT,KQ)
         CALL OPWEFF(RJ,KT,KQ,ETAO)
         CALL CALCPE(KT,PE)
         CALL JCNA(RJ,RJCNL,RJCNU)
         CALL REYCNA(R75R,R75RCL,R75RCU)
         CALL EXTCCN(Z,AEDVAO,TC75R,AEAOCL,AEAOCU,TC75CL,TC75CU)
         CALL BLPOW2(KQ,PCWBAL)
         CALL DICNUA(DIACNU)
         CALL CAVCNA(KT,AEACCV)
         CALL STRCNA(KQ,C75R,TCSTRS)
CC
CC       END OF EXECUTION PHASE
CC
      GO TO 3
    2 CONTINUE
C
C     OUTPUT-RESULT PHASE
C
         VK=V/1.688
         VAK=(1.0-WT)*VK
         PC=(2.0*PII*QS*N)/33000.0
         WRITE(6,9000)
         WRITE(6,9001)
         WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
         WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
         WRITE(6,9004)Z
         IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
            WRITE(6,9005)SC
         GO TO 86
   81    CONTINUE
         IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
```

```
          WRITE(6,9006)SC                                                 APP00970
      GO TO 86                                                            APP00980
   82 CONTINUE                                                            APP00990
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83                                    APP01000
          WRITE(6,9007)SC                                                 APP01010
      GO TO 86                                                            APP01020
   83 CONTINUE                                                            APP01030
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                                    APP01040
          WRITE(6,9008)SC                                                 APP01050
      GO TO 86                                                            APP01060
   84 CONTINUE                                                            APP01070
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                                    APP01080
          WRITE(6,9009)SC                                                 APP01090
      GO TO 86                                                            APP01100
   85 CONTINUE                                                            APP01110
          WRITE(6,9010)                                                   APP01120
   86 CONTINUE                                                            APP01130
      WRITE(6,9011)PE,V,VK,VAK,N,QS,PD,RJ,KT,KQ,ETAO,K75R,DIA,            APP01140
     1              PDIVD,AEDVAO,TC75R                                    APP01150
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN                                   APP01160
    3 CONTINUE                                                            APP01170
      RETURN                                                              APP01180
C                                                                         APP01190
C     MISCELLANEOUS FORMAT STATEMENTS                                     APP01200
C                                                                         APP01210
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 2',/,      APP01220
     1       1X,'                                SUBROUTINE "STRCNA"',//) APP01230
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R',/)            APP01240
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',      APP01250
     1       F10.4,/,                                                     APP01260
     2       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,             APP01270
     3       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,                APP01280
     4       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,         APP01290
     5       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)       APP01300
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,   APP01310
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,           APP01320
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,        APP01330
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,               APP01340
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,      APP01350
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)               APP01360
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',    APP01370
     1       F10.1)                                                       APP01380
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,                 APP01390
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP01400
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,                APP01410
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP01420
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                    APP01430
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP01440
```

```
9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,          APP01450
    1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01460
9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,       APP01470
    1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01480
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)         APP01490
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,     APP01500
    2       1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                       APP01510
    2       1X,29X,'V  (KNOTS )',23X,'=',F10.4,/,                       APP01520
    2       1X,29X,'VA (KNOTS )',23X,'=',F10.4,/,                       APP01530
    3       1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                       APP01540
    4       1X,29X,'CS (FT-LBF)',23X,'=',F12.1,/,                       APP01550
    5       1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                      APP01560
    6       1X,29X,'J          ',23X,'=',F10.4,/,                       APP01570
    7       1X,29X,'KT         ',23X,'=',F10.4,/,                       APP01580
    8       1X,29X,'KQ         ',23X,'=',F10.4,/,                       APP01590
    9       1X,29X,'ETAC       ',23X,'=',F10.4,/,                       APP01600
    A       1X,29X,'REY75R     ',23X,'=',E10.1,/,                       APP01610
    B       1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                       APP01620
    C       1X,29X,'P/D        ',23X,'=',F10.4,/,                       APP01630
    D       1X,29X,'AE/AO      ',23X,'=',F10.4,/,                       APP01640
    E       1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)                      APP01650
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP01660
    1       1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                         APP01670
    2       1X,29X,'MIN T/C .75R',22X,'=',F10.6)                        APP01680
      END                                                               APP01690
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,PDIVC,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD,VAK
      COMMON /GLOBCM/ETAC,WEIGHT,AEDVAO,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEACCL,AEACCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEACCV,ICSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC          SET "DESIGN CASE 2" PARAMETERS
CC
CC          ENVIRONMENTAL
CC
            TEMP=64.4
            WATRO=1.9892
            WATNU=.00001190O
            PATM=14.697
            PWATVA=.299439291
CC
CC          PROPELLER PARAMETERS
CC
            Z=6.0
            PROMAT=5.0
CC
CC          HULL PARAMETERS
CC
            WT=0.22
            TD=0.19
            ETARR=1.025
            NCSCRW=1.0
            HCL=21.9827
            DIALIM=30.0
CC
CC          SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
CC
```

```
      QS=121C129.835
      N=110.C
      VK=20.C641025E
      V=1.688*VK
CC
      END OF INPUT-INITIALIZATION PHASE
CC
   GO TO 3
C
   EXECUTION PHASE
C
 1 CONTINUE
   IF(.NOT.(ICALC.EQ.2))GO TO 2
      TC75R=((0.0185-0.00125*Z)*Z)/(2.073*AEDVAO)
      CALL RCCAL(DIA)
      CALL CH75RA(C75R)
      CALL REY75R(C75R,R75R)
      CALL COEFSA(RJ,R75R,KT,KQ)
      CALL OPWEFF(RJ,KT,KQ,ETAO)
      CALL CALCPE(KT,PE)
      CALL JCNA(RJ,RJCNL,RJCNU)
      CALL REYCNA(R75R,R75RCL,R75RCU)
      CALL EXTCCN(Z,AEDVAO,TC75R,AEACCL,AEADCU,TC75CL,TC75CU)
      CALL BLPOW2(KC,POWBAL)
      CALL DICNUA(DIACNU)
      CALL CAVCNA(KT,AEADCV)
      CALL STRCNK(KC,KT,C75R,TCSTRS)
CC
      END OF EXECUTION PHASE
CC
   GO TO 3
 2 CONTINUE
C
   OUTPUT-RESULT PHASE
C
      VK=V/1.688
      VAK=(1.0-WT)*VK
      PC=(2.0*PII*QS*N)/33000.0
      WRITE(6,9000)
      WRITE(6,9001)
      WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
      WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
      WRITE(6,9004)Z
      IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
         WRITE(6,9005)SC
      GO TO 86
81    CONTINUE
      IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
```

```
            WRITE(6,9006)SC                                            APP02680
         GO TO 86                                                      APP02690
   82    CONTINUE                                                      APP02700
         IF(.NOT.(PROMAT.EQ.3.0))GO TO 83                              APP02710
            WRITE(6,9007)SC                                            APP02720
         GO TO 86                                                      APP02730
   83    CONTINUE                                                      APP02740
         IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                              APP02750
            WRITE(6,9008)SC                                            APP02760
         GO TO 86                                                      APP02770
   84    CONTINUE                                                      APP02780
         IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                              APP02790
            WRITE(6,9009)SC                                            APP02800
         GO TO 86                                                      APP02810
   85    CONTINUE                                                      APP02820
            WRITE(6,9010)                                              APP02830
   86    CONTINUE                                                      APP02840
         WRITE(6,9011)PE,V,VK,VAK,N,QS,PD,RJ,KT,KQ,ETAO,R75R,DIA,      APP02850
     1             PDIVD,AEDVAO,TC75R                                  APP02860
         WRITE(6,9012)DIALIM,AEAOMN,TC75MN                             APP02870
    3 CONTINUE                                                         APP02880
      RETURN                                                           APP02890
C                                                                      APP02900
C     MISCELLANEOUS FORMAT STATEMENTS                                  APP02910
C                                                                      APP02920
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 2',/,   APP02930
     1       1X,'                             SUBROUTINE "STRCNK"',//) APP02940
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R',/)         APP02950
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',   APP02960
     1       F10.4,/,                                                  APP02970
     2       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,          APP02980
     3       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,             APP02990
     4       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,      APP03000
     5       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)    APP03010
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/, APP03020
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,        APP03030
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,     APP03040
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,            APP03050
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,   APP03060
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)            APP03070
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=', APP03080
     1       F10.1)                                                    APP03090
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,              APP03100
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)          APP03110
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,             APP03120
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)          APP03130
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                 APP03140
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)          APP03150
```

```
9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,              APP03160
   1        1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP03170
9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,          APP03180
   1        1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)             APP03190
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)            APP03200
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,        APP03210
   2        1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                         APP03220
   2        1X,29X,'V  (KNOTS )',23X,'=',F10.4,/,                         APP03230
   2        1X,29X,'VA (KNOTS )',23X,'=',F10.4,/,                         APP03240
   3        1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                         APP03250
   4        1X,29X,'CS (FT-LBF)',23X,'=',F12.1,/,                         APP03260
   5        1X,29X,'PD   (HP)  ',23X,'=',F10.2,//,                        APP03270
   6        1X,29X,'J          ',23X,'=',F10.4,/,                         APP03280
   7        1X,29X,'KT         ',23X,'=',F10.4,/,                         APP03290
   8        1X,29X,'KQ         ',23X,'=',F10.4,/,                         APP03300
   9        1X,29X,'ETAO       ',23X,'=',F10.4,/,                         APP03310
   A        1X,29X,'REY75R     ',23X,'=',E10.1,/,                         APP03320
   B        1X,29X,'DIA  (FT)  ',23X,'=',F10.4,/,                         APP03330
   C        1X,29X,'P/D        ',23X,'=',F10.4,/,                         APP03340
   D        1X,29X,'AE/AO      ',23X,'=',F10.4,/,                         APP03350
   E        1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)                        APP03360
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP03370
   1        1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                           APP03380
   2        1X,29X,'MIN T/C .75R',22X,'=',F10.6)                          APP03390
     END                                                                  APP03400
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVC,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEACCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KC,PD,VAK
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEACCV,TCSTRS,RJ
      COMMON /PARAM/VK,TC,WT,Z,WATRO,WATNU,TEMP,NCSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 2" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=64.4
           WATRO=1.9892
           WATNU=.000011900
           PATM=14.697
           PWATVA=.29943929I
CC
CC         PROPELLER PARAMETERS
CC
           Z=6.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TC=0.19
           ETARR=1.025
           NCSCRW=1.0
           HCL=21.9827
           DIALIM=30.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
CC
```

```
      QS=121C129.835                                                    APP03910
      N=110.0                                                           APP03920
CC                                                                      APP03930
CC         END OF INPUT-INITIALIZATION PHASE                            APP03940
CC                                                                      APP03950
      GO TO 3                                                           APP03960
C                                                                       APP03970
C     EXECUTION PHASE                                                   APP03980
C                                                                       APP03990
    1 CONTINUE                                                          APP04000
      IF(.NOT.(ICALC.EQ.2))GO TO 2                                      APP04010
            CALL RECAL(DIA)                                             APP04020
            CALL CH75RA(C75R)                                           APP04030
            CALL REY75R(C75R,R75R)                                      APP04040
            CALL COEFSA(RJ,R75R,KT,KQ)                                  APP04050
            CALL OPWEFF(RJ,KT,KQ,ETAO)                                  APP04060
            CALL CALCPE(KT,PE)                                          APP04070
            CALL JCNA(RJ,RJCNL,RJCNU)                                   APP04080
            CALL REYCNA(R75R,R75RCL,R75RCU)                             APP04090
            CALL EXTCCN(Z,AEDVAO,TC75R,AEAOCL,AEAOCU,TC75CL,TC75CU)     APP04100
            CALL BLPOW2(KC,POWBAL)                                      APP04110
            CALL DICNUA(DIACNU)                                         APP04120
            CALL CAVCNA(KT,AEAOCV)                                      APP04130
            CALL STRCNA(KC,C75R,TCSTRS)                                 APP04140
CC                                                                      APP04150
CC         END OF EXECUTION PHASE                                       APP04160
CC                                                                      APP04170
      GO TO 3                                                           APP04180
    2 CONTINUE                                                          APP04190
C                                                                       APP04200
C     OUTPUT-RESULT PHASE                                               APP04210
C                                                                       APP04220
            VK=V/1.688                                                  APP04230
            VAK=(1.0-WT)*VK                                             APP04240
            PD=(2.0*PII*QS*N)/33000.0                                   APP04250
            WRITE(6,9000)                                               APP04260
            WRITE(6,9001)                                               APP04270
            WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA                   APP04280
            WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM                  APP04290
            WRITE(6,9004)Z                                              APP04300
            IF(.NOT.(PROMAT.EQ.1.0))GO TO 81                            APP04310
                WRITE(6,9005)SC                                         APP04320
            GO TO 86                                                    APP04330
   81       CONTINUE                                                    APP04340
            IF(.NOT.(PROMAT.EQ.2.0))GO TO 82                            APP04350
                WRITE(6,9006)SC                                         APP04360
            GO TO 86                                                    APP04370
   82       CONTINUE                                                    APP04380
```

```
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83                                  APP04390
          WRITE(6,9007)SC                                               APP04400
      GO TO 86                                                          APP04410
   83 CONTINUE                                                          APP04420
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                                  APP04430
          WRITE(6,9008)SC                                               APP04440
      GO TO 86                                                          APP04450
   84 CONTINUE                                                          APP04460
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                                  APP04470
          WRITE(6,9009)SC                                               APP04480
      GO TO 86                                                          APP04490
   85 CONTINUE                                                          APP04500
          WRITE(6,9010)                                                 APP04510
   86 CONTINUE                                                          APP04520
      WRITE(6,9011)PE,V,VK,VAK,N,QS,PD,RJ,KT,KQ,ETAO,R75R,DIA,          APP04530
     1             PDIVD,AEDVAO,TC75R                                   APP04540
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN                                 APP04550
    3 CONTINUE                                                          APP04560
      RETURN                                                            APP04570
C                                                                       APP04580
C     MISCELLANEOUS FORMAT STATEMENTS                                   APP04590
C                                                                       APP04600
 9000 FORMAT('1','OPTIMIZATION RESULTS -----    DESIGN CASE NO. 2',/,   APP04610
     1      1X,'                                SUBROUTINE "STRCNA"',//) APP04620
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  QS,N',/)                  APP04630
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',    APP04640
     1      F10.4,/,                                                    APP04650
     1      1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,            APP04660
     2      1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,               APP04670
     3      1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,        APP04680
     4      1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)      APP04690
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/, APP04700
     1      1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,          APP04710
     2      1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,       APP04720
     3      1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,              APP04730
     4      1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,     APP04740
     5      1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)              APP04750
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',  APP04760
     1      F10.1)                                                      APP04770
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,               APP04780
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP04790
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,              APP04800
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP04810
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                  APP04820
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP04830
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,            APP04840
     1      1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP04850
 9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,         APP04860
```

```
     1        1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)               APP04870
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)                APP04880
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,            APP04890
     1        1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                          APP04900
     2        1X,29X,'V  (KNOTS )',23X,'=',F10.4,/,                          APP04910
     3        1X,29X,'VA (KNOTS )',23X,'=',F10.4,/,                          APP04920
     4        1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                          APP04930
     5        1X,29X,'QS (FT-LBF)',23X,'=',F12.1,/,                          APP04940
     6        1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                         APP04950
     7        1X,29X,'J          ',23X,'=',F10.4,/,                          APP04960
     8        1X,29X,'KT         ',23X,'=',F10.4,/,                          APP04970
     9        1X,29X,'KQ         ',23X,'=',F10.4,/,                          APP04980
     A        1X,29X,'ETAO       ',23X,'=',F10.4,/,                          APP04990
     B        1X,29X,'REY75R     ',23X,'=',E10.1,/,                          APP05000
     C        1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                          APP05010
     D        1X,29X,'P/D        ',23X,'=',F10.4,/,                          APP05020
     E        1X,29X,'AE/AO      ',23X,'=',F10.4,/,                          APP05030
     F        1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)                         APP05040
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP05050
     1        1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                            APP05060
     2        1X,29X,'MIN T/C .75R',22X,'=',F10.6)                           APP05070
      END                                                                    APP05080
```

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4  ETAO,WEIGHT,AEDVAD,DIA,N,PE,PDIVD,QS,TC75R,V,
     1        RJCNL,RJCNU,R75RCL,R75RCU,AEACCL,AEACCU,TC75CL,TC75CU,
     2        POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3        VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4        PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5        C75R,R75R,KT,KQ,PD,VAK
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAD,DIA,N,PE,PDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEACCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 2" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC          SET "DESIGN CASE 2" PARAMETERS
CC
CC          ENVIRONMENTAL
CC
            TEMP=64.4
            WATRO=1.9892
            WATNU=.00001190O
            PATM=14.697
            PWATVA=.29943929l
CC
CC          PROPELLER PARAMETERS
CC
            Z=6.0
            PROMAT=5.0
CC
CC          HULL PARAMETERS
CC
            WT=0.22
            TD=0.19
            ETARR=1.025
            NOSCRW=1.0
            HCL=21.9827
            DIALIM=30.0
CC
CC          SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 2"
CC
```

```
      QS=121(129.835
      N=110.C
CC
CC         END OF INPUT-INITIALIZATION PHASE
CC
      GO TO 3
C
C     EXECUTION PHASE
C
    1 CONTINUE
      IF(.NOT.(ICALC.EQ.2))GO TO 2
         CALL RCCAL(DIA)
         CALL CH75RA(C75R)
         CALL REY75R(C75R,R75R)
         CALL COEFSA(RJ,R75R,KT,KQ)
         CALL OPWEFF(RJ,KT,KQ,ETAO)
         CALL CALCPE(KT,PE)
         CALL JCNA(RJ,RJCNL,RJCNU)
         CALL REYCNA(R75R,R75RCL,R75RCU)
         CALL EXTCCN(Z,AEDVAO,TC75R,AEACCL,AEAOCU,TC75CL,TC75CU)
         CALL BLPOW2(KC,POWBAL)
         CALL DICNUA(DIACNU)
         CALL CAVCNA(KT,AEAOCV)
         CALL STRCNK(KC,KT,C75R,TCSTRS)
CC
CC         END OF EXECUTION PHASE
CC
      GO TO 3
    2 CONTINUE
C
C     OUTPUT-RESULT PHASE
C
         VK=V/1.688
         VAK=(1.0-WT)*VK
         PC=(2.C*PII*QS*N)/33000.0
         WRITE(6,9000)
         WRITE(6,9001)
         WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
         WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
         WRITE(6,9004)Z
         IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
            WRITE(6,9005)SC
         GO TO 86
   81    CONTINUE
         IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
            WRITE(6,9006)SC
         GO TO 86
   82    CONTINUE
```

```
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83                                  APP06070
          WRITE(6,9007)SC                                               APP06080
      GO TO 86                                                          APP06090
   83 CONTINUE                                                          APP06100
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84                                  APP06110
          WRITE(6,9008)SC                                               APP06120
      GO TO 86                                                          APP06130
   84 CONTINUE                                                          APP06140
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85                                  APP06150
          WRITE(6,9009)SC                                               APP06160
      GO TO 86                                                          APP06170
   85 CONTINUE                                                          APP06180
          WRITE(6,9010)                                                 APP06190
   86 CONTINUE                                                          APP06200
      WRITE(6,9011)PE,V,VK,VAK,N,QS,PD,RJ,KT,KQ,ETAO,R75R,DIA,          APP06210
     1             PDIVD,AEDVAO,TC75R                                   APP06220
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN                                 APP06230
    3 CONTINUE                                                          APP06240
      RETURN                                                            APP06250
C                                                                       APP06260
C     MISCELLANEOUS FORMAT STATEMENTS                                   APP06270
C                                                                       APP06280
 9000 FORMAT('1','OPTIMIZATION RESULTS -----    DESIGN CASE NO. 2',/,   APP06290
     1       1X,'                               SUBROUTINE "STRONK"',//)APP06300
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  QS,N',/)                  APP06310
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',    APP06320
     1       F10.4,/,                                                   APP06330
     1       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,           APP06340
     2       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,              APP06350
     3       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,       APP06360
     4       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)     APP06370
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/, APP06380
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,         APP06390
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,      APP06400
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,             APP06410
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,    APP06420
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)             APP06430
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',  APP06440
     1       F10.1)                                                     APP06450
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,               APP06460
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,//)          APP06470
 9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,              APP06480
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,//)          APP06490
 9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                  APP06500
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,//)          APP06510
 9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,            APP06520
     1       1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,//)          APP06530
 9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,         APP06540
```

```
    1         1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)              APP06550
 9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)              APP06560
 9011 FORMAT(1X,' SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,         APP06570
    1         1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                         APP06580
    2         1X,29X,'V  (KNOTS )',23X,'=',F10.4,/,                         APP06590
    3         1X,29X,'VA (KNOTS )',23X,'=',F10.4,/,                         APP06600
    4         1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                         APP06610
    5         1X,29X,'CS (FT-LBF)',23X,'=',F12.1,/,                         APP06620
    6         1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                        APP06630
    7         1X,29X,'J          ',23X,'=',F10.4,/,                         APP06640
    8         1X,29X,'KT         ',23X,'=',F10.4,/,                         APP06650
    9         1X,29X,'KQ         ',23X,'=',F10.4,/,                         APP06660
    A         1X,29X,'ETAC       ',23X,'=',F10.4,/,                         APP06670
    B         1X,29X,'REY75R     ',23X,'=',E10.1,/,                         APP06680
    C         1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                         APP06690
    D         1X,29X,'P/D        ',23X,'=',F10.4,/,                         APP06700
    E         1X,29X,'AE/AO      ',23X,'=',F10.4,/,                         APP06710
    F         1X,29X,'T/C  .75R  ',23X,'=',F10.4,//)                        APP06720
 9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP06730
    1         1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                           APP06740
    2         1X,29X,'MIN T/C .75R',22X,'=',F10.6)                          APP06750
      END                                                                   APP06760
```

APPENDIX G

CONTROL CARD IMAGES--DESIGN CASE NO. 2

```
$A   TITLE
  WAGENINGEN B-SERIES PROPELLER CPTIMIZATION
$B    NCALC          NDV         NSV       N2VAR      NXAPRX     IPNPUT      IPDBG
          2            3                                              0
$C   IPRINT        ITMAX      ICNDIR       NSCAL        ITRM     LINOBJ     NACMX1
          1         1C00                      -1          3C                    15
$D1    FDCH        FDCHM          CT       CTMIN         CTL     CTLMIN      THETA
     0.0001       0.0C01       -.001
$D2  DELFUN       CABFUN      ALPHAX      ABOBJI

$E   NDVTOT         ICBJ      SGNCPT
          3            1         1.0
$F      VLB          VUB           X        SCAL
        0.4          1.1        0.40         1.0
       0.01          1.1         0.1         1.0
        0.4          1.4         1.0         1.0
$G   NDSSGN        IDSGN       AMULT
          1            3         1.0
          2           23         1.0
          3            7         1.0
$H    NCONS
         10
$I1    ICON         JCON        LCON
$I2      BL        SCAL1          BU       SCAL2
         11           11
-1.0    +16          1.0         0.0         1.0
         12           12
-1.0    +16          1.0         0.0         1.0
         13           13
-1.0    +16          1.0         0.0         1.0
         14           14
-1.0    +16          1.0         0.0         1.0
         15           15
-1.0    +16          1.0         0.0         1.0
         16           16
-1.0    +16          1.0         0.0         1.0
         17           17
-1.0    +16          1.0         0.0         1.0
         18           18
-1.0    +16          1.0         0.0         1.0
         19           19
-1.0    +16          1.0         0.0         1.0
         21           21
-1.0    +16          1.0         0.0         1.0
$V
END
```

```
$A   TITLE
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
$B    NCALC        NDV        NSV      N2VAR      NXAPRX     IPNPUT      IPDBG
          2          5                                           0
$C   IPRINT      ITMAX     ICNDIR      NSCAL       ITRM     LINOBJ     NACMX1
          1       1000                    -1         30                    15
$D1    FDCH      FDCHM         CT      CTMIN        CTL     CTLMIN      THETA
     0.0001     0.0001      -.001
$D2  DELFUN     DABFUN     ALPHAX     ABOBJI

$E   NDVTOT       IOBJ     SGNOPT
          5          1        1.0
$F      VLB        VUB          X       SCAL
        0.4        1.1       0.40        1.0
       0.01        1.1        0.1        1.0
        0.4        1.4        1.0        1.0
       10.0      100.0       50.0       10.0
      0.003        0.5     0.0500       0.01
$G   NDSSGN      IDSGN      AMULT
          1          3        1.0
          2         23        1.0
          3          7        1.0
          4         10        1.0
          5          9        1.0
$H    NCONS
         12
$I1    ICON       JCON       LCON
$I2      BL      SCAL1         BU      SCAL2
         11         11
-1.0    +16        1.0        0.0        1.0
         12         12
-1.0    +16        1.0        0.0        1.0
         13         13
-1.0    +16        1.0        0.0        1.0
         14         14
-1.0    +16        1.0        0.0        1.0
         15         15
-1.0    +16        1.0        0.0        1.0
         16         16
-1.0    +16        1.0        0.0        1.0
         17         17
-1.0    +16        1.0        0.0        1.0
         18         18
-1.0    +16        1.0        0.0        1.0
         19         19
-1.0    +16        1.0        0.0        1.0
         20         20
-1.0    +16        1.0        0.0        1.0
```

```
          21           21
-1.0    +16          1.0          0.0          1.0
          22           22
-1.0    +16          1.0          0.0          1.0
$V
END
```

APPENDIX H

COPES OUTPUT--DESIGN CASE NO. 2

COPES

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                    IMAGE

  1)   $A   TITLE
  2)      WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)   $E    NCALC        NDV        NSV       N2VAR      NXAPRX     IPNPLT      IPDBG
  4)             2          3
  5)   $C   IPRINT       ITMAX      ICNDIR      NSCAL       ITRM      LINOEJ     NALMXI
  6)             1        1000                    -1         30                     15
  7)   $C1    FDCH       FDCHM         CT       CTMIN        CTL      CTLMIN      THETA
  8)        0.0001      0.0001      -.001
  9)   $C2  DELFUN      DABFUN     ALPHAX      ABOBJI
 10)
 10)
 11)   $E   NCVTOT        IOBJ     SGNOPT
 12)             3           1        1.0
 13)   $F      VLB         VUB          X        SCAL
 14)           0.4         1.1       C.40        1.0
 15)          0.01         1.1        0.1        1.0
 16)           0.4         1.4        1.0        1.0
 17)   $G   NCSSGN       IDSGN      APULT
 18)             1           3        1.0
 19)             2          23        1.0
 20)             3           7        1.0
 21)   $F    NCONS
 22)            10
 23)   $I1    ICON        JCCN       LCON
 24)   $I2      BL       SCAL1         BU       SCAL2
 25)            11          11
 26)   -1.0    +16         1.0        0.0         1.0
 27)            12          12
 28)   -1.C    +16         1.0        0.0         1.0
 29)            13          13
 30)   -1.C    +16         1.0        0.0         1.0
 31)            14          14
 32)   -1.C    +16         1.0        0.0         1.0
 33)            15          15
 34)   -1.C    +16         1.0        0.0         1.0
 35)            16          16
 36)   -1.C    +16         1.0        0.0         1.0
 37)            17          17
 38)   -1.C    +16         1.0        0.0         1.0
 39)            18          18
 40)   -1.0    +16         1.0        0.0         1.0
 41)            19          19
 42)   -1.C    +16         1.0        0.0         1.0
 43)            21          21
 44)   -1.C    +16         1.0        0.0         1.0
 45)   $V
 46)   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS;
CALCULATION CONTROL,                       NCALC  =     6
NUMBER OF GLOBAL DESIGN VARIABLES,           NDV  =     3
NUMBER OF SENSITIVITY VARIABLES,             NSV  =     0
NUMBER OF FUNCTIONS IN TWO-SPACE,          N2VAR  =     0
NUMBER OF APPROXIMATING VAR.              NXAPRX  =     0
INPUT INFORMATION PRINT CODE,             IPNPUT  =     0
DEBUG PRINT CODE,                          IFDBG  =     0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                    =  1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)  =  0.10000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX    ICNDIR    NSCAL    ITRM    LINOBJ   NACMX1    NFEG
 1      1000      0        -1       30       0       15         0

 FDCH            FDCHM            CT                CTMIN
 0.10000E-02     0.10000E-03      -0.10000E-02      0.0

 CTL             CTLMIN           THETA             PHI
 0.0             0.0              0.0               0.0

 DELFUN          DABFUN           ALPHAX            ABOBJ1
 0.0             0.0              0.0               0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.       LOWER           UPPER            INITIAL
NO.         BOUND           BOUND            VALUE            SCALE
  1      0.40000E+00     0.11000E+01     0.40000E+00     0.10000E+01
  2      0.10000E-01     0.11000E+01     0.10000E+00     0.10000E+01
  3      0.40000E+00     0.14000E+01     0.10000E+01     0.10000E+01

DESIGN VARIABLES
        D. V.       GLOBAL       MULTIPLYING
ID      NO.        VAR. NO.        FACTOR
 1       1            3         0.10000E+01
 2       2           23         0.10000E+01
 3       3            7         0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 10 CONSTRAINT SETS
      GLOBAL   GLOBAL   LINEAR       LOWER        NORMALIZATION      UPPER        NORMALIZATION
 ID   VAR. 1   VAR. 2    ID          BOUND           FACTOR          BOUND           FACTOR
  1     11       11       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  2     12       12       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  3     13       13       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  4     14       14       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  5     15       15       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  6     16       16       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  7     17       17       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  8     18       18       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
  9     19       19       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01
 10     21       21       0       -0.11000E+16    0.10000E+01      0.0            0.10000E+01

TOTAL NUMBER OF CONSTRAINED PARAMETERS =   10
```

REAL			INTEGER		
INPUT	EXECUTION	AVAILABLE	INPUT	EXECUTION	AVAILABLE
67	490	10000	43	104	1000

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 2
                             SUBROUTINE "STRLNA"

DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                         =    64.4000
                             DENSITY (LBF-SEC2/FT4)               =     1.9892
                             VISCOSITY (FT2/SEC)                  = 0.118999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)          =    14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)   =     0.2594

HULL PARAMETERS:             WAKE FRACTION                        =     0.2200
                             THRUST DEDUCTION FRACTION            =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY         =     1.0250
                             NUMBER OF PROPELLERS                 =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)       =    21.9827
                             DIAMETER LIMIT (FT)                  =    30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                     =        6.0
                             MATERIAL TYPE                        =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)               =     5400.0

SELECTION VALUES:            PE (HP)                              =5752440.0
                             V  (FT/SEC)                          =    33.8682
                             V  (KNOTS)                           =    20.0641
                             VA (KNOTS)                           =    15.6500
                             N  (RPM)                             =   110.0000
                             QS (FT-LBF)                          =   1210130.0
                             PD  (HP)                             =   25344.90

                             J                                    =     0.1000
                             KT                                   =     0.4001
                             KQ                                   =     0.0539
                             ETAC                                 =     0.1182
                             REY75R                               =    0.1E+10
                             DIA (FT)                             =   144.0937
                             P/D                                  =     1.0000
                             AE/AO                                =     0.4000
                             T/C .75R                             =     0.0796

CONSTRAINT VALUES:           MAX DIA (FT)                         =    30.0000
                             MIN AE/AO                            =    45.4788
                             MIN T/C .75R                         =   0.062820
```

```
 * * * * * * * * * * * * * * * * * * * * * * * * *
 *                                                 *
 *                  C O N M I N                    *
 *              FORTRAN PROGRAM FOR                *
 *        CONSTRAINED FUNCTION MINIMIZATION        *
 *                                                 *
 * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.118204E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.40000E+00  0.10000E+00  0.10000E+01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.62500E-01 -0.93750E+00 -0.52026E+03 -0.47874E+03  0.10000E+00 -0.40000E+00
  7)    -0.55696E-01 -0.47757E-01 -0.99996E+00  0.12270E+03
```

```
FINAL OPTIMIZATION INFORMATION

OBJ =  -0.665992E+00

DECISION VARIABLES (X-VECTOR)
  1)     0.80177E+00  0.64752E+00  0.50364E+00

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.40470E+00 -0.59530E+00 -0.24820E+02 -0.97418E+03 -0.30178E+00  0.17773E-02
  7)    -0.15810E-01 -0.87642E-01 -0.24307E-02 -0.36772E+00

THERE ARE    2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
     6    9

THERE ARE    0 VIOLATED CONSTRAINTS

THERE ARE    0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION
     ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

NUMBER OF ITERATIONS =    45

OBJECTIVE FUNCTION WAS EVALUATED          230  TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED       230  TIMES
```

CPTIMIZATION RESULTS

CBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.66599E+00

CESIGN VARIABLES

ID	D. V. NC.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	C.40000E+00	0.80177E+00	0.11000E+01
2	2	23	C.10000E-01	0.64752E+00	0.11000E+01
3	3	7	0.40000E+00	0.90364E+00	0.14000E+01

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.40470E+00	0.0
2	12	-0.11000E+16	-0.59530E+00	0.0
3	13	-0.11000E+16	-0.24821E+02	0.0
4	14	-0.11000E+16	-0.97418E+03	0.0
5	15	-0.11000E+16	-0.30177E+00	0.0
6	16	-0.11000E+16	0.17748E-C2	0.0
7	17	-0.11000E+16	-0.19811E-01	0.0
8	18	-0.11000E+16	-0.87642E-01	0.0
9	19	-0.11000E+16	-0.24527E-02	0.0
10	21	-C.11000E+16	-0.36771E+00	0.0

```
OPTIMIZATICN RESULTS ------- DESIGN CASE NO. 2
                             SUBROUTINE "STRCNA"

DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =     64.4000
                             DENSITY (LBF-SEC2/FT4)                =      1.9892
                             VISCOSITY (FT2/SEC)                   = 0.118999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =     14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)    =      0.2994

HULL PARAMETERS:             WAKE FRACTION                         =      0.2200
                             THRUST DEDUCTION FRACTION             =      0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =      1.0250
                             NUMBER OF PROPELLERS                  =         1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =     21.9827
                             DIAMETER LIMIT (FT)                   =     30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =         6.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =      5400.0

SELECTION VALUES:            PE  (HP)                              =     14057.3
                             V   (FT/SEC)                          =     33.8682
                             V   (KNOTS )                          =     20.0641
                             VA  (KNOTS )                          =     15.6500
                             N   (RPM)                             =    110.0000
                             QS  (FT-LBF)                          =   1210130.0
                             PD   (HP)                             =    25344.90

                             J                                     =      0.6475
                             KT                                    =      0.1719
                             KQ                                    =      0.0266
                             ETAC                                  =      0.6660
                             REY75R                                =     0.5E+08
                             DIA (FT)                              =     22.2533
                             P/D                                   =      0.9036
                             AE/AC                                 =      0.8018
                             T/C .75R                              =      0.0397

CONSTRAINT VALUES:           MAX DIA (FT)                          =     30.0000
                             MIN AE/AO                             =      0.5070
                             MIN T/C .75R                          =   0.027297
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	231
3	2

```
CCCCCCC   COOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS

           C O N T R O L   P R O G R A M
                       F O R
        E N G I N E E R I N G   S Y N T H E S I S


                      T I T L E
       WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
```

CARD IMAGES OF CONTROL DATA

```
CARD                    IMAGE

  1)   $A   TITLE
  2)     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)   $B     NCALC         NGV          NSV        N2VAR      NXAPRX     IPNPLT      IPDBG
  4)              2           3                                              0
  5)   $C    IPRINT       ITMAX       ICNDIR        NSCAL       ITRM     LINOBJ     NALMXI
  6)              1        1000                        -1         30                   15
  7)   $C1     FDCH       FDCHM           CT        CTMIN        CTL     CTLMIN      THETA
  8)         0.0001      0.0001        -.001
  9)   $C2   DELFUN      DABFUN       ALPHAX       ABOBJ1
 10)
 10)
 11)   $E    NDVTOT        IOBJ       SGNOPT
 12)              3           1          1.0
 13)   $F       VLB         VUB            X         SCAL
 14)            0.4         1.1         0.40          1.0
 15)           0.01         1.1          0.1          1.0
 16)            0.4         1.4          1.0          1.0
 17)   $G    NDSSGN       IDSGN        AMULT
 18)              1           3          1.0
 19)              2          23          1.0
 20)              3           7          1.0
 21)   $H     NCONS
 22)             10
 23)   $I1     ICON        JCON         LCON
 24)   $I2       BL       SCAL1           BU        SCAL2
 25)             11          11
 26)   -1.0     +16         1.0          0.0          1.0
 27)             12          12
 28)   -1.0     +16         1.0          0.0          1.0
 29)             13          13
 30)   -1.0     +16         1.0          0.0          1.0
 31)             14          14
 32)   -1.0     +16         1.0          0.0          1.0
 33)             15          15
 34)   -1.0     +16         1.0          0.0          1.0
 35)             16          16
 36)   -1.0     +16         1.0          0.0          1.0
 37)             17          17
 38)   -1.0     +16         1.0          0.0          1.0
 39)             18          18
 40)   -1.0     +16         1.0          0.0          1.0
 41)             19          19
 42)   -1.0     +16         1.0          0.0          1.0
 43)             21          21
 44)   -1.0     +16         1.0          0.0          1.0
 45)   $\
 46)   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                    NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,        NDV =    3
NUMBER OF SENSITIVITY VARIABLES,          NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,       N2VAR =    0
NUMBER OF APPROXIMATING VAR,           NXAPRX =    0
INPUT INFORMATION PRINT CODE,          IPNPUT =    0
DEBUG PRINT CODE,                       IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                   =  1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)  =  0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT   ITMAX   ICNDIR   NSCAL   ITRM   LINOBJ   NACMX1   NFDG
  1      1000      0       -1      30      0       15        0

 FDCH              FDCHM              CT                 CTMIN
 0.10000E-03       0.10000E-03       -0.10000E-02        0.0

 CTL               CTLMIN             THETA              PHI
 0.0               0.0                0.0                0.0

 DELFUN            DABFUN             ALPHAX             ABOBJ1
 0.0               0.0                0.0                0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER             UPPER             INITIAL
NO.        BOUND             BOUND              VALUE               SCALE
  1      0.40000E+00      0.11000E+01      0.40000E+00      0.10000E+01
  2      0.10000E-01      0.11000E+01      0.10000E+00      0.10000E+01
  3      0.40000E+00      0.14000E+01      0.10000E+01      0.10000E+01

DESIGN VARIABLES
        D. V.      GLOBAL       MULTIPLYING
ID      NO.      VAR. NO.         FACTOR
 1       1           3         0.10000E+01
 2       2          23         0.10000E+01
 3       3           7         0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 10 CONSTRAINT SETS
       GLOBAL   GLOBAL   LINEAR       LOWER       NORMALIZATION      UPPER        NORMALIZATION
 ID    VAR. 1   VAR. 2     ID         BOUND          FACTOR          BOUND           FACTOR
  1      11       11       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  2      12       12       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  3      13       13       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  4      14       14       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  5      15       15       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  6      16       16       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  7      17       17       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  8      18       18       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
  9      19       19       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01
 10      21       21       0      -0.11000E+16    0.10000E+01      0.0           0.10000E+01

TOTAL NUMBER OF CONSTRAINED PARAMETERS =    10
```

	REAL			INTEGER	
INPUT	EXECUTION	AVAILABLE	INPUT	EXECUTION	AVAILABLE
67	490	10000	43	104	1000

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 2
                             SUBROUTINE "STRCNR"

DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                              =    64.4000
                             DENSITY (LBF-SEC2/FT4)                    =     1.9692
                             VISCOSITY (FT2/SEC)                       = 0.1189999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)               =    14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)        =     0.2994

HULL PARAMETERS:             WAKE FRACTION                             =     0.2200
                             THRUST DEDUCTION FRACTION                 =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY              =     1.0250
                             NUMBER OF PROPELLERS                      =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)            =    21.9827
                             DIAMETER LIMIT (FT)                       =    30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                          =        6.0
                             MATERIAL TYPE                             =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                    =     5400.0

SELECTION VALUES:            PE  (HP)                                  =57525440.0
                             V   (FT/SEC)                              =    33.8662
                             V   (KNOTS )                              =    20.0641
                             VA  (KNOTS )                              =    15.6500
                             N   (RPM)                                 =   110.0000
                             QS  (FT-LBF)                              =  1210130.0
                             PD  (HP)                                  =   25344.90

                             J                                         =     0.1000
                             KT                                        =     0.4001
                             KQ                                        =     0.0539
                             ETAC                                      =     0.1182
                             REY75R                                    =    0.1E+10
                             DIA (FT)                                  =   144.0937
                             P/D                                       =     1.0000
                             AE/AO                                     =     0.4000
                             T/C .75R                                  =     0.0796

CONSTRAINT VALUES:           MAX DIA (FT)                              =    30.0000
                             MIN AE/AO                                 =    49.4788
                             MIN T/C .75R                              =   0.179593
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*                   C O N M I N                     *
*                                                   *
*             FORTRAN PROGRAM FOR                   *
*                                                   *
*       CONSTRAINED FUNCTION MINIMIZATION           *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.118204E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.40000E+00  0.10000E+00  0.10000E+01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.62500E-01 -0.53750E+00 -0.52026E+03 -0.47874E+03  0.10000E+00 -0.40000E+00
  7)   -0.55696E-01 -0.47757E-01 -0.59996E+00  0.12270E+03
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =   -0.665992E+00

 DECISION VARIABLES (X-VECTOR)
   1)     0.80177E+00  0.64752E+00  0.50364E+00

 CONSTRAINT VALUES (G-VECTOR)
   1)    -0.40470E+00 -0.59530E+00 -0.24820E+02 -0.97418E+03 -0.30178E+00  0.17773E-02
   7)    -0.15810E-01 -0.87642E-01 -0.24307E-02 -0.36772E+00

 THERE ARE    2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
      6    5

 THERE ARE    0 VIOLATED CONSTRAINTS

 THERE ARE    0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

 NUMBER OF ITERATIONS =   45

 OBJECTIVE FUNCTION WAS EVALUATED          230  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED       230  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.66599E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.40000E+00	0.80177E+00	0.11000E+01
2	2	23	0.10000E-01	0.64752E+00	0.11000E+01
3	3	7	0.40000E+00	0.90364E+00	0.14000E+01

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.40470E+00	0.0
2	12	-0.11000E+16	-0.59530E+00	0.0
3	13	-0.11000E+16	-0.24821E+02	0.0
4	14	-0.11000E+16	-0.97418E+03	0.0
5	15	-0.11000E+16	-0.30177E+00	0.0
6	16	-0.11000E+16	0.17748E-02	0.0
7	17	-0.11000E+16	-0.19811E-01	0.0
8	18	-0.11000E+16	-0.87642E-01	0.0
9	19	-0.11000E+16	-0.24527E-02	0.0
10	21	-0.11000E+16	-0.36771E+00	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 2
                             SUBROUTINE "STRCNK"

DESIGN VARIABLES SPECIFIED:  QS,N,V,TC75R

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                         =    64.4000
                             DENSITY (LBF-SEC2/FT4)               =     1.9892
                             VISCOSITY (FT2/SEC)                  = 0.1189999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)          =    14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)   =     0.2994

HULL PARAMETERS:             WAKE FRACTION                        =     0.2200
                             THRUST DEDUCTION FRACTION            =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY         =     1.0250
                             NUMBER OF PROPELLERS                 =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)       =    21.9827
                             DIAMETER LIMIT (FT)                  =    30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                     =        6.0
                             MATERIAL TYPE                        =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)               =     5400.0

SELECTION VALUES:            PE  (HP)                             =    14057.3
                             V   (FT/SEC)                         =    33.8682
                             V   (KNOTS )                         =    20.0641
                             VA  (KNOTS )                         =    15.6500
                             N   (RPM)                            =   110.0000
                             QS  (FT-LBF)                         =  1210133.0
                             PD   (HP)                            =   25344.90

                             J                                    =     0.6475
                             KT                                   =     0.1719
                             KQ                                   =     0.0266
                             ETAO                                 =     0.6660
                             REY75R                               =   0.5E+08
                             DIA (FT)                             =    22.2533
                             P/D                                  =     0.9036
                             AE/AO                                =     0.8018
                             T/C .75R                             =     0.0397

CONSTRAINT VALUES:           MAX DIA (FT)                         =    30.0000
                             MIN AE/AO                            =     0.5070
                             MIN T/C .75R                         =   0.064709
```

```
PROGRAM CALLS TO ANALIZ

   ICALC    CALLS
     1          1
     2        231
     3          2
```

```
CCCCCCC   OOOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                          IMAGE

  1|  $A  TITLE
  2|     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3|  $B   NCALC        NCV        NSV       N2VAR     NXAPRX     IPNPUT      IPDBG
  4|          2          5                                            0
  5|  $C  IPRINT      ITMAX      ICNDIR     NSCAL       ITRM     LINOBJ     NACMX1
  6|          1       1000                    -1         30                    15
  7|  $C1   FDCH      FDCHM         CT      CTMIN        CTL     CTLMIN      THETA
  8|     0.0001     0.0001      -.001
  9|  $C2 DELFUN     DABFUN     ALPHAX     ABOBJ1
 10|
 10|
 11|  $E  NCVTOT       IOBJ     SGNOPT
 12|          5          1        1.0
 13|  $F    VLB        VUB          X       SCAL
 14|        0.4        1.1       0.40        1.0
 15|       0.01        1.1        0.1        1.0
 16|        0.4        1.4        1.0        1.0
 17|       10.0      100.0       50.0       10.0
 18|      0.003        0.5     0.0500       0.01
 19|  $G  NCSSGN     IDSGN      AMULT
 20|          1          3        1.0
 21|          2         23        1.0
 22|          3          7        1.0
 23|          4         10        1.0
 24|          5          9        1.0
 25|  $H    NCONS
 26|         12
 27|  $I1   ICON       JCON       ICON
 28|  $I2     BL      SCAL1         BU      SCAL2
 29|         11         11
 30|  -1.0   +16        1.0        0.0        1.0
 31|         12         12
 32|  -1.0   +16        1.0        0.0        1.0
 33|         13         13
 34|  -1.0   +16        1.0        0.0        1.0
 35|         14         14
 36|  -1.0   +16        1.0        0.0        1.0
 37|         15         15
 38|  -1.0   +16        1.0        0.0        1.0
 39|         16         16
 40|  -1.0   +16        1.0        0.0        1.0
 41|         17         17
 42|  -1.0   +16        1.0        0.0        1.0
 43|         18         18
 44|  -1.0   +16        1.0        0.0        1.0
 45|         19         19
 46|  -1.0   +16        1.0        0.0        1.0
 47|         20         20
 48|  -1.0   +16        1.0        0.0        1.0
 49|         21         21
 50|  -1.0   +16        1.0        0.0        1.0
 51|         22         22
 52|  -1.0   +16        1.0        0.0        1.0
 53|  $V
 54|  END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                        NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,            NDV =    5
NUMBER OF SENSITIVITY VARIABLES,              NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,           N2VAR =    0
NUMBER OF APPROXIMATING VAR.               NXAPRX =    0
INPUT INFORMATION PRINT CODE,              IPNPUT =    0
DEBUG PRINT CODE,                           IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE     MEANING
  1       SINGLE ANALYSIS
  2       OPTIMIZATION
  3       SENSITIVITY
  4       TWO-VARIABLE FUNCTION SPACE
  5       OPTIMUM SENSITIVITY
  6       APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                     =    1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)  =   0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT   ITMAX    ICNDIR    NSCAL    ITRM    LINOBJ   NACMX1   NFDG
  1      1000       0        -1      30        0       15        0

 FDCH               FDCHM              CT                 CTMIN
 0.10000E-03        0.10000E-03        -0.10000E-02       0.0

 CTL                CTLMIN             THETA              PHI
 0.0                0.0                0.0                0.0

 DELFUN             DABFUN             ALPHAX             ABOBJ1
 0.0                0.0                0.0                0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.       LOWER            UPPER            INITIAL
NO.         BOUND            BOUND            VALUE            SCALE
  1      0.40000E+00      0.11000E+01      0.40000E+00      0.10000E+01
  2      0.10000E-01      0.11000E+01      0.10000E+00      0.10000E+01
  3      0.40000E+00      0.14000E+01      0.10000E+01      0.10000E+01
  4      0.10000E+02      0.10000E+03      0.50000E+02      0.10000E+02
  5      0.30000E-02      0.50000E+00      0.50000E-01      0.10000E-01

 DESIGN VARIABLES
         D. V.       GLOBAL      MULTIPLYING
ID        NO.       VAR. NO.        FACTOR
 1         1           3         0.1000E+01
 2         2          23         0.1000E+01
 3         3           7         0.1000E+01
 4         4          10         0.1000E+01
 5         5           9         0.1000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
       GLOBAL   GLOBAL   LINEAR        LOWER        NORMALIZATION     UPPER       NORMALIZATION
 ID    VAR. 1   VAR. 2     ID          BOUND           FACTOR         BOUND          FACTOR
  1      11       11       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  2      12       12       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  3      13       13       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  4      14       14       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  5      15       15       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  6      16       16       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  7      17       17       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  8      18       18       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
  9      15       19       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
 10      20       20       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
 11      21       21       0       -0.11000E+16    0.10000E+01     0.0          0.10000E+01
```

```
TOTAL NUMBER OF CONSTRAINED PARAMETERS =    12


* * ESTIMATED DATA STORAGE REQUIREMENTS

          REAL                                   INTEGER
INPUT   EXECUTION   AVAILABLE        INPUT   EXECUTION   AVAILABLE
  87       570        10000            57        124        1000
```

```
OPTIMIZATION RESULTS -----   DESIGN CASE NO. 2
                             SUBROUTINE "STRONA"

DESIGN VARIABLES SPECIFIED:  QS,N

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =    64.4000
                             DENSITY (LBF-SEC2/FT4)                =     1.9892
                             VISCOSITY (FT2/SEC)                   = 0.1169999?7E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =    14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)    =     0.2994

HULL PARAMETERS:             WAKE FRACTION                         =     0.2200
                             THRUST DEDUCTION FRACTION             =     0.1900
                             RELATIVE ROTATIVE EFFICIENCY          =     1.0250
                             NUMBER OF PROPELLERS                  =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =    21.9627
                             DIAMETER LIMIT (FT)                   =    30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =        6.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =     5400.0

SELECTION VALUES:            PE  (HP)                              =***********
                             V   (FT/SEC)                          =    50.0000
                             V   (KNOTS )                          =    29.6208
                             VA  (KNOTS )                          =    23.1042
                             N   (RPM)                             =   110.0000
                             QS  (FT-LBF)                          =   1210130.0
                             PD   (HP)                             =   25344.50

                             J                                     =     0.1000
                             KT                                    =     0.4002
                             KQ                                    =     0.0538
                             ETAO                                  =     0.1184
                             REY75R                                =   0.4E+10
                             DIA (FT)                              =   212.7272
                             P/D                                   =     1.0000
                             AE/AO                                 =     0.4000
                             T/C .75R                              =     0.0500

CONSTRAINT VALUES:           MAX DIA (FT)                          =    30.0000
                             MIN AE/AO                             =   107.8435
                             MIN T/C .75R                          =   0.062794
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                 *
*                   C C N M I N                   *
*                                                 *
*               FORTRAN PROGRAM FOR               *
*                                                 *
*         CONSTRAINED FUNCTION MINIMIZATION       *
*                                                 *
* * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =  -0.118442E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.40000E+00  0.10000E+00  0.10000E+01  0.50000E+02  0.50000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.62500E-01 -0.93750E+00 -0.17803E+04  0.78128E+03  0.10000E+00 -0.40000E+00
  7)   -0.30101E-01 -0.77352E-01 -0.99999E+00  0.60909E+01  0.26661E+03  0.25585E+00
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =  -0.757645E+00

 DECISION VARIABLES (X-VECTOR)
   1)    0.79462E+00  0.99270E+00  0.11986E+01  0.52182E+02  0.49512E-01

 CONSTRAINT VALUES (G-VECTOR)
   1)   -0.62044E+00 -0.37956E+00 -0.23017E+02 -0.97558E+03 -0.29462E+00 -0.53805E-02
   7)   -0.30014E-01 -0.77435E-01 -0.36019E-03 -0.25451E+00 -0.41625E+00 -0.45777E+00

 THERE ARE    2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     6    9

 THERE ARE    0 VIOLATED CONSTRAINTS

 THERE ARE    0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR 30 ITERATIONS
      ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

 NUMBER OF ITERATIONS =   80

 OBJECTIVE FUNCTION WAS EVALUATED          544  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED       544  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.75764E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.40000E+00	0.79462E+00	0.11000E+01
2	2	23	0.10000E-01	0.99270E+00	0.11000E+01
3	3	7	0.40000E+00	0.11986E+01	0.14000E+01
4	4	10	0.10000E+02	0.52182E+02	0.10000E+03
5	5	9	0.30000E-02	0.49912E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.62044E+00	0.0
2	12	-0.11000E+16	-0.37956E+00	0.0
3	13	-0.11000E+16	-0.23017E+02	0.0
4	14	-0.11000E+16	-0.57598E+03	0.0
5	15	-0.11000E+16	-0.25462E+00	0.0
6	16	-0.11000E+16	-0.53822E-02	0.0
7	17	-0.11000E+16	-0.30014E-01	0.0
8	18	-0.11000E+16	-0.77439E-01	0.0
9	19	-0.11000E+16	-0.23633E-03	0.0
10	20	-0.11000E+16	-0.25452E+00	0.0
11	21	-0.11000E+16	-0.41832E+00	0.0
12	22	-0.11000E+16	-0.45777E+00	0.0

```
OPTIMIZATION RESULTS -----    DESIGN CASE NO. 2
                              SUBROUTINE "STRONA"

DESIGN VARIABLES SPECIFIED:   QS,N

ENVIRONMENTAL PARAMETERS:     TEMP (DEG F)                          =   64.4000
                              DENSITY (LBF-SEC2/FT4)                =    1.9892
                              VISCOSITY (FT2/SEC)                   = 0.1189999997E-04
                              ATMOSPHERIC PRESSURE (PSIA)           =   14.6970
                              WATER VAPORIZATION PRESSURE (PSIA)    =    0.2994

HULL PARAMETERS:              WAKE FRACTION                         =    0.2200
                              THRUST DEDUCTION FRACTION             =    0.1900
                              RELATIVE ROTATIVE EFFICIENCY          =    1.0250
                              NUMBER OF PROPELLERS                  =       1.0
                              DEPTH TO SHAFT CENTERLINE (FT)        =   21.9827
                              DIAMETER LIMIT (FT)                   =   30.0000

PROPELLER PARAMETERS:         NUMBER OF BLADES                      =       6.0
                              MATERIAL TYPE                         =  STAINLESS STEEL
                              ALLOWABLE STRESS (PSI)                =    5400.0

SELECTION VALUES:             PE  (HP)                              =   19945.5
                              V   (FT/SEC)                          =   52.1824
                              V   (KNOTS )                          =   30.9138
                              VA  (KNOTS )                          =   24.1127
                              N   (RPM)                             =  110.0000
                              QS  (FT-LBF)                          =  1210130.0
                              PD  (HP)                              =  25344.90

                              J                                     =    0.5927
                              KT                                    =    0.1552
                              KQ                                    =    0.0324
                              ETAO                                  =    0.7576
                              REY75R                                =   0.5E+08
                              DIA (FT)                              =   22.3645
                              P/D                                   =    1.1986
                              AE/AO                                 =    0.7946
                              T/C .75R                              =    0.0499

CONSTRAINT VALUES:            MAX DIA (FT)                          =   30.0000
                              MIN AE/AO                             =    0.4622
                              MIN T/C .75R                          =  0.027064
```

PROGRAM CALLS TO ANALIZ

ICALL	CALLS
1	1
2	545
3	2

```
CCCCCCC   OOOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                   IMAGE

  1|   $A   TITLE
  2|      WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3|   $E    KCALC         NDV        NSV       N2VAR      NXAPRX     IPNPLT     IPDBG
  4|             2           5                                          0
  5|   $C   IPRINT       ITMAX      ICNDIR     NSCAL       ITRM      LINCEJ     NACMX1
  6|             1        1000                    -1         30                   15
  7|   $C1    FDCH       FDCHM         CT      CTMIN        CTL      CTLMIN     THETA
  8|        0.0001      0.0001      -.001
  9|   $C2  DELFUN      DABFUN     ALPHAX     ABOBJ1
 10|
 10|
 11|   $E   NDVTOT        IOBJ     SGNOPT
 12|             5           1        1.0
 13|   $F      VLB         VUB          X      SCAL
 14|           0.4         1.1       0.40       1.0
 15|          0.01         1.1        0.1       1.0
 16|           0.4         1.4        1.0       1.0
 17|          10.0       100.0       50.0      10.0
 18|         0.003         0.5     0.0500      0.01
 19|   $G   NDSSGN       IDSGN      AMULT
 20|             1           3        1.0
 21|             2          23        1.0
 22|             3           7        1.0
 23|             4          10        1.0
 24|             5           9        1.0
 25|   $H    NCONS
 26|            12
 27|   $I1    ICON        JCON       LCON
 28|   $I2      BL       SCAL1         BU     SCAL2
 29|            11          11
 30|   -1.0    +16         1.0        0.0       1.0
 31|            12          12
 32|   -1.0    +16         1.0        0.0       1.0
 33|            13          13
 34|   -1.0    +16         1.0        0.0       1.0
 35|            14          14
 36|   -1.0    +16         1.0        0.0       1.0
 37|            15          15
 38|   -1.0    +16         1.0        0.0       1.0
 39|            16          16
 40|   -1.0    +16         1.0        0.0       1.0
 41|            17          17
 42|   -1.0    +16         1.0        0.0       1.0
 43|            18          18
 44|   -1.0    +16         1.0        0.0       1.0
 45|            19          19
 46|   -1.0    +16         1.0        0.0       1.0
 47|            20          20
 48|   -1.0    +16         1.0        0.0       1.0
 49|            21          21
 50|   -1.0    +16         1.0        0.0       1.0
 51|            22          22
 52|   -1.0    +16         1.0        0.0       1.0
 53|   $V
 54|   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                        NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,            NDV =    5
NUMBER OF SENSITIVITY VARIABLES,              NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,           N2VAR =    0
NUMBER OF APPROXIMATING VAR.               NXAPRX =    0
INPUT INFORMATION PRINT CODE,              IPNPUT =    0
DEBUG PRINT CODE,                           IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE   MEANING
  1     SINGLE ANALYSIS
  2     OPTIMIZATION
  3     SENSITIVITY
  4     TWO-VARIABLE FUNCTION SPACE
  5     OPTIMUM SENSITIVITY
  6     APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE              =    1
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION)  =   0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX   ICNDIR   NSCAL    ITRM   LINOBJ  NACMX1   NFDG
  1     1000      0       -1       30       0      15       0

 FDCH             FDCHM            CT               CTMIN
 0.10000E-02      0.10000E-02      0.0              0.0

 CTL              CTLMIN           THETA            PHI
 0.0              0.0              0.0              0.0

 DELFUN           DABFUN           ALPHAX           ABOBJ1
 0.0              0.0              0.0              0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.     LOWER            UPPER           INITIAL
NO.       BOUND            BOUND            VALUE             SCALE
 1      0.20000E+00      0.11000E+01     0.30000E+00      0.10000E+01
 2      0.10000E+01      0.50000E+02     0.30000E+02      0.10000E+02
 3      0.0              0.10000E+08     0.10000E+00      0.10000E+01
 4      0.40000E+00      0.14000E+01     0.50000E+00      0.10000E+01
 5      0.30000E-02      0.50000E+00     0.30000E-01      0.10000E-01

DESIGN VARIABLES
      D. V.      GLOBAL       MULTIPLYING
ID     NO.      VAR. NO.        FACTOR
 1      1           3        0.10000E+01
 2      2           4        0.10000E+01
 3      3          23        0.10000E+01
 4      4           7        0.10000E+01
 5      5           9        0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
      GLOBAL   GLOBAL   LINEAR        LOWER          NORMALIZATION        UPPER            NORMALIZATION
ID    VAR. 1   VAR. 2     ID          BOUND              FACTOR           BOUND               FACTOR
 1      11       11        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 2      12       12        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 3      13       13        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 4      14       14        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 5      15       15        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 6      16       16        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 7      17       17        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 8      18       18        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
 9      19       19        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
10      20       20        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
11      21       21        0       -0.11000E+16      0.10000E+01      0.0                0.10000E+01
```

```
OPTIMIZATION RESULTS -----   DESIGN CASE NO. 2
                             SUBROUTINE "STRCNK"

DESIGN VARIABLES SPECIFIED:  QS,N

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                             =   64.4000
                             DENSITY (LBF-SEC2/FT4)                   =    1.9892
                             VISCOSITY (FT2/SEC)                      = 0.1189999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)              =   14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)       =    0.2994

HULL PARAMETERS:             WAKE FRACTION                            =    0.2200
                             THRUST DEDUCTION FRACTION                =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY             =    1.0250
                             NUMBER OF PROPELLERS                     =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)           =   21.9827
                             DIAMETER LIMIT (FT)                      =   30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                         =       6.0
                             MATERIAL TYPE                            =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                   =    5400.0

SELECTION VALUES:            PE  (HP)                                 =**********
                             V   (FT/SEC)                             =   50.0000
                             V   (KNOTS )                             =   29.6208
                             VA  (KNOTS )                             =   23.1042
                             N   (RPM)                                =  110.0000
                             QS  (FT-LBF)                             =  1210130.0
                             PD  (HP)                                 =  25344.90

                             J                                        =    0.1000
                             KT                                       =    0.4002
                             KQ                                       =    0.0538
                             ETAO                                     =    0.1184
                             REY75R                                   =   0.4E+10
                             DIA (FT)                                 =  212.7272
                             P/D                                      =    1.0000
                             AE/AO                                    =    0.4000
                             T/C .75R                                 =    0.0500

CONSTRAINT VALUES:           MAX DIA (FT)                             =   30.0000
                             MIN AE/AO                                =  107.8435
                             MIN T/C .75R                             =  0.179593
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                 *
*                  C O N M I N                    *
*                                                 *
*              FORTRAN PROGRAM FOR                *
*                                                 *
*       CONSTRAINED FUNCTION MINIMIZATION         *
*                                                 *
* * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =   -0.118442E+00

DECISION VARIABLES (X-VECTOR)
  1)     0.40000E+00  0.10000E+00  0.10000E+01  0.50000E+02  0.50000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.62500E-01 -0.93750E+00 -0.17803E+04  0.78128E+03  0.10000E+00 -0.40000E+00
  7)    -0.30101E-01 -0.77352E-01 -0.59999E+00  0.60909E+01  0.26601E+03  0.25919E+01
```

```
FINAL OPTIMIZATION INFORMATION

OBJ =  -0.732977E+00

DECISION VARIABLES (X-VECTOR)
  1)    0.75858E+00  0.87525E+00  0.10308E+01  0.49656E+02  0.63838E-01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.54704E+00 -0.45296E+00 -0.22551E+02 -0.97645E+03 -0.29659E+00 -0.14130E-02
  7)   -0.43940E-01 -0.63513E-01 -0.66166E-01 -0.19217E+00 -0.46566E+00  0.45776E-03

THERE ARE    2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
    6   12

THERE ARE    0 VIOLATED CONSTRAINTS

THERE ARE    0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION
     ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

NUMBER OF ITERATIONS =   35

OBJECTIVE FUNCTION WAS EVALUATED          209  TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED       209  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 1 FUNCTION VALUE 0.73297E+00

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.40000E+00	0.79858E+00	0.11000E+01
2	2	23	0.10000E-01	0.87525E+00	0.11000E+01
3	3	7	0.40000E+00	0.10308E+01	0.14000E+01
4	4	10	0.10000E+02	0.49856E+02	0.10000E+03
5	5	9	0.30000E-02	0.63838E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.54703E+00	0.0
2	12	-0.11000E+16	-0.45257E+00	0.0
3	13	-0.11000E+16	-0.22551E+02	0.0
4	14	-0.11000E+16	-0.57645E+03	0.0
5	15	-0.11000E+16	-0.25858E+00	0.0
6	16	-0.11000E+16	-0.14159E-02	0.0
7	17	-0.11000E+16	-0.43935E-01	0.0
8	18	-0.11000E+16	-0.63514E-01	0.0
9	19	-0.11000E+16	-0.65962E-01	0.0
10	20	-0.11000E+16	-0.19218E+00	0.0
11	21	-0.11000E+16	-0.46577E+00	0.0
12	22	-0.11000E+16	0.46730E-03	0.0

```
OPTIMIZATION RESULTS -----   DESIGN CASE NO. 2
                             SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:  QS,N

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                             =   64.4000
                             DENSITY (LBF-SEC2/FT4)                   =    1.9892
                             VISCOSITY (FT2/SEC)                      = 0.1189999997E-04
                             ATMOSPHERIC PRESSURE (PSIA)              =   14.6970
                             WATER VAPORIZATION PRESSURE (PSIA)       =    0.2994

HULL PARAMETERS:             WAKE FRACTION                            =    0.2200
                             THRUST DEDUCTION FRACTION                =    0.1900
                             RELATIVE ROTATIVE EFFICIENCY             =    1.0250
                             NUMBER OF PROPELLERS                     =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)           =   21.9827
                             DIAMETER LIMIT (FT)                      =   30.0000

PROPELLER PARAMETERS:        NUMBER OF BLADES                         =       6.0
                             MATERIAL TYPE                            = STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                   =    5400.0

SELECTION VALUES:            PE  (HP)                                 =   20653.7
                             V   (FT/SEC)                             =   45.8560
                             V   (KNOTS )                             =   25.5355
                             VA  (KNOTS )                             =   23.0377
                             N   (RPM)                                =  110.0000
                             QS  (FT-LBF)                             = 1210130.0
                             PD  (HP)                                 =  25344.90

                             J                                        =    0.8753
                             KT                                       =    0.1220
                             KQ                                       =    0.0232
                             ETAO                                     =    0.7330
                             REY75R                                   =   0.5E+08
                             DIA (FT)                                 =   24.2346
                             P/D                                      =    1.0308
                             AE/AO                                    =    0.7986
                             T/C .75R                                 =    0.0638

CONSTRAINT VALUES:           MAX DIA (FT)                             =   30.0000
                             MIN AE/AO                                =    0.4266
                             MIN T/C .75R                             =  0.063868
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	210
3	2

APPENDIX I

ANALIZ CODES--DESIGN CASE NO. 3

```
      SUBROUTINE ANALIZ(ICALC)
      INTEGER*4 ICALC
      REAL*4 ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,
     1       RJCNL,RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,
     2       POWBAL,DIACNU,AEAOCV,TCSTRS,RJ,
     3       VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,
     4       PWATVA,PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC,
     5       C75R,R75R,KT,KQ,PD,TDEV,PTDEV,PEDEV,CREQ,PDREQ
      COMMON /GLOBCM/ETAO,WEIGHT,AEDVAO,DIA,N,PE,FDIVD,QS,TC75R,V,RJCNL,
     1RJCNU,R75RCL,R75RCU,AEAOCL,AEAOCU,TC75CL,TC75CU,POWBAL,DIACNU,
     2AEAOCV,TCSTRS,RJ
      COMMON /PARAM/VK,TD,WT,Z,WATRO,WATNU,TEMP,NOSCRW,HCL,PATM,PWATVA,
     1PROMAT,DIALIM,ETARR,AEAOMN,TC75MN,SC
C
C     THIS SUBROUTINE, COUPLED WITH COPES/CONMIN, CONSTITUTES ANALYSIS
C     METHOD FOR "DESIGN CASE 3" PROPELLER SELECTION PROBLEMS
C
C     INPUT-INITIALIZATION PHASE
C
      PII=3.14159264
      IF(.NOT.(ICALC.EQ.1))GO TO 1
CC
CC         SET "DESIGN CASE 3" PARAMETERS
CC
CC         ENVIRONMENTAL
CC
           TEMP=59.0
           WATRO=1.9905
           WATNU=.000012817
           PATM=14.7
           PWATVA=.247
CC
CC         PROPELLER PARAMETERS
CC
           Z=6.0
           PROMAT=5.0
CC
CC         HULL PARAMETERS
CC
           WT=0.22
           TD=0.1725
           ETARR=1.025
           NOSCRW=1.0
           HCL=19.0
CC
CC         SET DESIGN VARIABLES HELD FIXED FOR "DESIGN CASE 3"
CC
           PE=21292.6
```

```
      VK=24.24
      V=1.688*VK
      N=105.0
      QS=1500606.75
      DIA=22.0
CC
CC         END OF INPUT-INITIALIZATION PHASE
CC
      GO TO 3
C
C     EXECUTION PHASE
C
    1 CONTINUE
      IF(.NOT.(ICALC.EQ.2))GO TO 2
           CALL RJCAL(RJ)
           CALL CH75RA(C75R)
           CALL REY75R(C75R,R75R)
           CALL COEFSA(RJ,R75R,KT,KQ)
           CALL OPWEFF(RJ,KT,KQ,ETAO)
           CALL JCNA(RJ,RJCNL,RJCNU)
           CALL REYCNA(R75R,R75RCL,R75RCU)
           CALL EXTCCN(Z,AEDVAO,TC75R,AEAOCL,AEAOCU,TC75CL,TC75CU)
           CALL BLPOW3(KT,KQ,POWBAL,DIACNU)
           CALL CAVCNA(KT,AEAOCV)
           CALL STRCNK(KQ,KT,C75R,TCSTRS)
           CALL WGTCAL(C75R)
CC
CC         END OF EXECUTION PHASE
CC
      GO TO 3
    2 CONTINUE
C
C     OUTPUT-RESULT PHASE
C
           PE=(2.0*PII*QS*N)/33000.0
           TDEV=(KT*WATRO*(DIA**4)*((N/60.0)**2))
           PTDEV=(TDEV*((1.0-WT)*V))/550.0
           PEDEV=((((1.0-TD)/(1.0-WT))*ETARR*PTDEV)*NOSCRW)
           QREQ=(KQ*WATRO*(DIA**5)*((N/60.0)**2))
           PEREQ=(2.0*PII*QREQ*N)/33000.0
           ETAOSP=(((1.0-WT)/(1.0-TD))*(((PE/NOSCRW)*33000.0)/ETARR))/
     1           (2.0*PII*QS*N)
           WRITE(6,9000)
           WRITE(6,9001)
           WRITE(6,9002)TEMP,WATRO,WATNU,PATM,PWATVA
           WRITE(6,9003)WT,TD,ETARR,NOSCRW,HCL,DIALIM
           WRITE(6,9004)Z
           IF(.NOT.(PROMAT.EQ.1.0))GO TO 81
```

```
      WRITE(6,9005)SC
      GO TO 86
 81   CONTINUE
      IF(.NOT.(PROMAT.EQ.2.0))GO TO 82
         WRITE(6,9006)SC
      GO TO 86
 82   CONTINUE
      IF(.NOT.(PROMAT.EQ.3.0))GO TO 83
         WRITE(6,9007)SC
      GO TO 86
 83   CONTINUE
      IF(.NOT.(PROMAT.EQ.4.0))GO TO 84
         WRITE(6,9008)SC
      GO TO 86
 84   CONTINUE
      IF(.NOT.(PROMAT.EQ.5.0))GO TO 85
         WRITE(6,9009)SC
      GO TO 86
 85   CONTINUE
         WRITE(6,9010)
 86   CONTINUE
      WRITE(6,9011)PE,V,N,QS,PD,ETACSP,RJ,KT,KQ,ETAO,R75R,DIA,
     1             PDIVD,AEDVAO,TC75R,WEIGHT
      WRITE(6,9012)DIALIM,AEAOMN,TC75MN
      WRITE(6,9013)PEDEV,VK,QREC,N,PCREC
    3 CONTINUE
      RETURN
C
C     MISCELLANEOUS FORMAT STATEMENTS
C
 9000 FORMAT('1','OPTIMIZATION RESULTS ------- DESIGN CASE NO. 3',/
     1       1X,'                               SUBROUTINE "STRCNK"',//)
 9001 FORMAT(1X,'DESIGN VARIABLES SPECIFIED:  PE,V,QS,N,DIA',/)
 9002 FORMAT(1X,'ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)',22X,'=',
     1       F10.4,/,
     1       1X,29X,'DENSITY (LBF-SEC2/FT4)',12X,'=',F10.4,/,
     2       1X,29X,'VISCOSITY (FT2/SEC)',15X,'=',E16.9,/,
     3       1X,29X,'ATMOSPHERIC PRESSURE (PSIA)',7X,'=',F10.4,/,
     4       1X,29X,'WATER VAPORIZATION PRESSURE (PSIA)=',F10.4,//)
 9003 FORMAT(1X,'HULL PARAMETERS:',13X,'WAKE FRACTION',21X,'=',F10.4,/,
     1       1X,29X,'THRUST DEDUCTION FRACTION',9X,'=',F10.4,/,
     2       1X,29X,'RELATIVE ROTATIVE EFFICIENCY',6X,'=',F10.4,/,
     3       1X,29X,'NUMBER OF PROPELLERS',14X,'=',F10.1,/,
     4       1X,29X,'DEPTH TO SHAFT CENTERLINE (FT)',4X,'=',F10.4,/,
     5       1X,29X,'DIAMETER LIMIT (FT)',15X,'=',F10.4,//)
 9004 FORMAT(1X,'PROPELLER PARAMETERS:',8X,'NUMBER OF BLADES',18X,'=',
     1       F10.1)
 9005 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST IRON',/,
```

```
     1          1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01450
9006 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  CAST STEEL',/,                   APP01460
     1          1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01470
9007 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  BRONZE',/,                       APP01480
     1          1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01490
9008 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NI-AL BRONZE',/,                 APP01500
     1          1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01510
9009 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  STAINLESS STEEL',/,              APP01520
     1          1X,29X,'ALLOWABLE STRESS (PSI)',12X,'=',F10.1,/)            APP01530
9010 FORMAT(1X,29X,'MATERIAL TYPE',21X,'=  NOT CONSIDERED',/)               APP01540
9011 FORMAT(1X,'SELECTION VALUES:',12X,'PE (HP)',27X,'=',F10.1,/,           APP01550
     2          1X,29X,'V  (FT/SEC)',23X,'=',F10.4,/,                       APP01560
     3          1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                       APP01570
     4          1X,29X,'QS (FT-LBF)',23X,'=',F12.1,/,                       APP01580
     5          1X,29X,'PD  (HP)   ',23X,'=',F10.2,//,                      APP01590
     6          1X,29X,'ETAO SPECIFIED',20X,'=',F10.4,//,                   APP01600
     7          1X,29X,'J          ',23X,'=',F10.4,/,                       APP01610
     8          1X,29X,'KT         ',23X,'=',F10.4,/,                       APP01620
     9          1X,29X,'KQ         ',23X,'=',F10.4,/,                       APP01630
     A          1X,29X,'ETAO       ',23X,'=',F10.4,/,                       APP01640
     B          1X,29X,'REY75R     ',23X,'=',E10.1,/,                       APP01650
     C          1X,29X,'DIA (FT)   ',23X,'=',F10.4,/,                       APP01660
     D          1X,29X,'P/D        ',23X,'=',F10.4,/,                       APP01670
     E          1X,29X,'AE/AO      ',23X,'=',F10.4,/,                       APP01680
     F          1X,29X,'T/C  .75R  ',23X,'=',F10.4,/,                       APP01690
     G          1X,29X,'BLADE WEIGHT (LBF)',16X,'=',F10.1,//)               APP01700
9012 FORMAT(1X,'CONSTRAINT VALUES:',11X,'MAX DIA (FT)',22X,'=',F10.4,/,APP01710
     1          1X,29X,'MIN AE/AO',25X,'=',F10.4,/,                         APP01720
     2          1X,29X,'MIN T/C .75R',22X,'=',F10.6,//)                     APP01730
9013 FORMAT(1X,'PROPELLER "POINTS":',10X,'PE DEVELOPED (HP)',17X,'=',       APP01740
     1          F10.1,/,                                                    APP01750
     2          1X,29X,'V  (KNOTS) ',23X,'=',F10.4,//,                      APP01760
     3          1X,29X,'QS REQUIRED (FT-LBF)',14X,'=',F12.1,/,              APP01770
     4          1X,29X,'N  (RPM)   ',23X,'=',F10.4,/,                       APP01780
     5          1X,29X,'PD REQUIRED (HP)',18X,'=',F10.2,/////)              APP01790
      END                                                                   APP01800
```

APPENDIX J

CONTROL CARD IMAGES--DESIGN CASE NO. 3

```
$A   TITLE
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
$B     NCALC         NDV         NSV       N2VAR      NXAPRX     IPNPUT      IPDBG
           2           3                                              0
$C   IPRINT        ITMAX      ICNDIR      NSCAL       ITRM     LINOBJ     NACMX1
           1        1000                     -1         30                    15
$D1    FDCH        FDCHM          CT      CTMIN        CTL     CTLMIN      THETA
       .001         .001        -.01
$D2  DELFUN       DABFUN      ALPHAX     ABOBJI

$E   NDVTOT         IOBJ      SGNOPT
           3           2        -1.0
$F      VLB          VUB           X       SCAL
        0.2          1.1        1.00        1.0
        0.4          1.4         1.3        1.0
      0.003          0.5      0.0100      0.100
$G   NDSSGN        IDSGN       AMULT
          1            3         1.0
          2            7         1.0
          3            9         1.0
$H    NCONS
         12
$I1    ICON         JCON        LCON
$I2      BL        SCAL1          BU      SCAL2
         11           11
-1.0    +16          1.0         0.0        1.0
         12           12
-1.0    +16          1.0         0.0        1.0
         13           13
-1.0    +16          1.0         0.0        1.0
         14           14
-1.0    +16          1.0         0.0        1.0
         15           15
-1.0    +16          1.0         0.0        1.0
         16           16
-1.0    +16          1.0         0.0        1.0
         17           17
-1.0    +16          1.0         0.0        1.0
         18           18
-1.0    +16          1.0         0.0        1.0
         19           19
-1.0    +16          1.0         0.0        1.0
         20           20
-1.0    +16          1.0         0.0        1.0
         21           21
-1.0    +16          1.0         0.0        1.0
         22           22
-1.0    +16          1.0         0.0        1.0
```

```
$V
END
```

APPENDIX K

COPES OUTPUT--DESIGN CASE NO. 3

COPES

C O N T R O L   P R O G R A M
F O R
E N G I N E E R I N G   S Y N T H E S I S

T I T L E
WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                     IMAGE

  1)   $A   TITLE
  2)     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)   $E    NCALC         NDV          NSV        N2VAR     NXAPRX      IPNPLT      IPDBG
  4)             2           3                                              0
  5)   $C   IPRINT       ITMAX       ICNDIR      NSCAL       ITRM      LINOBJ     NACMX1
  6)             1        1000                     -1          30                    15
  7)   $C1    FDCH       FDCHM           CT      CTMIN        CTL      CTLMIN      THETA
  8)          .001        .001         -.01
  9)   $C2  DELFUN      DABFUN       ALPHAX     ABOBJ1
 10)
 10)
 11)   $E   NCVTOT        IOBJ       SGNOPT
 12)             3           2         -1.0
 13)   $F      VLB         VUB            X       SCAL
 14)           0.2         1.1         1.00        1.0
 15)           0.4         1.4          1.3        1.0
 16)         0.003         0.5       0.0100      0.100
 17)   $G   NDSSGN       IDSGN        AMULT
 18)             1           3          1.0
 19)             2           7          1.0
 20)             3           9          1.0
 21)   $H    NCONS
 22)            12
 23)   $I1    ICON        JCON         LCON
 24)   $I2      BL       SCAL1           BU      SCAL2
 25)            11          11
 26)   -1.0    +16         1.0          0.0        1.0
 27)            12          12
 28)   -1.0    +16         1.0          0.0        1.0
 29)            13          13
 30)   -1.0    +16         1.0          0.0        1.0
 31)            14          14
 32)   -1.0    +16         1.0          0.0        1.0
 33)            15          15
 34)   -1.0    +16         1.0          0.0        1.0
 35)            16          16
 36)   -1.0    +16         1.0          0.0        1.0
 37)            17          17
 38)   -1.0    +16         1.0          0.0        1.0
 39)            18          18
 40)   -1.0    +16         1.0          0.0        1.0
 41)            19          19
 42)   -1.0    +16         1.0          0.0        1.0
 43)            20          20
 44)   -1.0    +16         1.0          0.0        1.0
 45)            21          21
 46)   -1.0    +16         1.0          0.0        1.0
 47)            22          22
 48)   -1.0    +16         1.0          0.0        1.0
 49)   $J
 50)   END
```

```
TITLE:
  WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                        NCALC =    2
NUMBER OF GLOBAL DESIGN VARIABLES,            NDV =    3
NUMBER OF SENSITIVITY VARIABLES,              NSV =    0
NUMBER OF FUNCTIONS IN TWO-SPACE,           N2VAR =    0
NUMBER OF APPROXIMATING VAR.               NXAPRX =    0
INPUT INFORMATION PRINT CODE,              IPNPUT =    0
DEBUG PRINT CODE,                           IPDBG =    0

CALCULATION CONTROL, NCALC
VALUE    MEANING
  1        SINGLE ANALYSIS
  2        OPTIMIZATION
  3        SENSITIVITY
  4        TWO-VARIABLE FUNCTION SPACE
  5        OPTIMUM SENSITIVITY
  6        APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE               =     2
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) = -0.1000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX   ICNDIR   NSCAL    ITRM   LINOBJ  NACMX1   NFDG
  1     1000      0       -1       30      0       15       0

 FDCH            FDCHM           CT                 CTMIN
 0.10000E-02     0.10000E-02     -0.10000E-01       0.0

 CTL             CTLMIN          THETA              PHI
 0.0             0.0             0.0                0.0

 DELFUN          DABFUN          ALPHAX             ABOBJ1
 0.0             0.0             0.0                0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER           UPPER           INITIAL
NO.        BOUND           BOUND           VALUE            SCALE
  1      0.20000E+00     0.11000E+01     0.10000E+01     0.10000E+01
  2      0.40000E+00     0.14000E+01     0.13000E+01     0.10000E+01
  3      0.30000E-02     0.50000E+00     0.10000E-01     0.10000E+00

DESIGN VARIABLES
         D. V.     GLOBAL       MULTIPLYING
ID        NO.     VAR. NO.        FACTOR
 1         1         3          0.10000E+01
 2         2         7          0.10000E+01
 3         3         9          0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
        GLOBAL   GLOBAL   LINEAR         LOWER         NORMALIZATION        UPPER        NORMALIZATION
 ID     VAR. 1   VAR. 2     ID           BOUND            FACTOR            BOUND           FACTOR
  1       11       11        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  2       12       12        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  3       13       13        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  4       14       14        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  5       15       15        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  6       16       16        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  7       17       17        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  8       18       18        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
  9       19       19        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
 10       20       20        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
 11       21       21        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01
 12       22       22        0       -0.11000E+16      0.10000E+01        0.0           0.10000E+01

TOTAL NUMBER OF CONSTRAINED PARAMETERS =    12
```

```
* * ESTIMATED DATA STORAGE REQUIREMENTS

              REAL                                         INTEGER
INPUT   EXECUTION   AVAILABLE          INPUT   EXECUTION   AVAILABLE
  75        504       10000              49       112        1000
```

```
OPTIMIZATION RESULTS -------  DESIGN CASE NO. 3
                              SUBROUTINE "STRCNK"

DESIGN VARIABLES SPECIFIED:   PE,V,QS,N,DIA

ENVIRONMENTAL PARAMETERS:     TEMP (DEG F)                             =   55.0000
                              DENSITY (LBF-SEC2/FT4)                   =    1.9905
                              VISCOSITY (FT2/SEC)                      = 0.128170304E-04
                              ATMOSPHERIC PRESSURE (PSIA)              =   14.7000
                              WATER VAPORIZATION PRESSURE (PSIA)       =    0.2470

HULL PARAMETERS:              WAKE FRACTION                            =    0.2200
                              THRUST DEDUCTION FRACTION                =    0.1725
                              RELATIVE ROTATIVE EFFICIENCY             =    1.0250
                              NUMBER OF PROPELLERS                     =       1.0
                              DEPTH TO SHAFT CENTERLINE (FT)           =   15.0000
                              DIAMETER LIMIT (FT)                      =    0.0

PROPELLER PARAMETERS:         NUMBER OF BLADES                         =       6.0
                              MATERIAL TYPE                            =  STAINLESS STEEL
                              ALLOWABLE STRESS (PSI)                   =   5400.0

SELECTION VALUES:             PE  (HP)                                 =  21292.6
                              V   (FT/SEC)                             =  40.9171
                              N   (RPM)                                = 105.0000
                              QS  (FT-LBF)                             =  1500607.0
                              PD  (HP)                                 = 30000.05

                              ETAC SPECIFIED                           =    0.6527

                              J                                        =    0.8290
                              KT                                       =    0.2980
                              KQ                                       =    0.0597
                              ETAC                                     =    0.6585
                              REY75R                                   =  0.8E+08
                              DIA (FT)                                 =  22.0000
                              P/D                                      =   1.3000
                              AE/AO                                    =   1.0000
                              T/C .75R                                 =   0.0100
                              BLADE WEIGHT (LBF)                       =   2563.1

CONSTRAINT VALUES:            MAX DIA (FT)                             =    0.0
                              MIN AE/AO                                =   1.0266
                              MIN T/C .75R                             = 0.054838

PROPELLER "POINTS":           PE DEVELOPED (HP)                        =  24856.6
                              V   (KNOTS)                              =  24.2400

                              QS REQUIRED (FT-LBF)                     =  1875936.0
                              N   (RPM)                                = 105.0000
                              PD REQUIRED (HP)                         = 37503.62
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                   *
*                  C O N M I N                      *
*                                                   *
*               FORTRAN PROGRAM FOR                 *
*                                                   *
*        CONSTRAINED FUNCTION MINIMIZATION          *
*                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =    0.256313E+04

DECISION VARIABLES (X-VECTOR)
  1)     0.10000E+01  0.13000E+01  0.10000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.51811E+00 -0.48185E+00 -0.36758E+02 -0.96224E+03 -0.50000E+00  0.20000E+00
  7)    0.98987E-02 -0.24470E+00 -0.26131E+00  0.25012E+00  0.26567E-01  0.44838E+01
```

```
FINAL OPTIMIZATION INFORMATION

 OBJ =    0.128426E+05

 DECISION VARIABLES (X-VECTOR)
   1)    0.79444E+00  0.11813E+01  0.79389E-01

 CONSTRAINT VALUES (G-VECTOR)
   1)   -0.51811E+00 -0.48189E+00 -0.13450E+02 -0.98555E+03 -0.29444E+00 -0.55616E-02
   7)   -0.59491E-01 -0.17531E+00  0.58407E-02 -0.61652E-01  0.71621E-01 -0.12991E+00

 THERE ARE     1 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     6

 THERE ARE     2 VIOLATED CONSTRAINTS
 CONSTRAINT NUMBERS ARE
     9   11

 THERE ARE     0 ACTIVE SIDE CONSTRAINTS

 TERMINATION CRITERION
      TEN CONSECUTIVE ITERATIONS FAILED TO PRODUCE A FEASIBLE DESIGN

 NUMBER OF ITERATIONS =    10

 OBJECTIVE FUNCTION WAS EVALUATED           37  TIMES

 CONSTRAINT FUNCTIONS WERE EVALUATED        37  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 2 FUNCTION VALUE 0.12843E+05

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.20000E+00	0.79444E+00	0.11000E+01
2	2	7	0.40000E+00	0.11813E+01	0.14000E+01
3	3	9	0.30000E-02	0.79389E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.51811E+00	0.0
2	12	-0.11000E+16	-0.48185E+00	0.0
3	13	-0.11000E+16	-0.13450E+02	0.0
4	14	-0.11000E+16	-0.58555E+03	0.0
5	15	-0.11000E+16	-0.29444E+00	0.0
6	16	-0.11000E+16	-0.55616E-02	0.0
7	17	-0.11000E+16	-0.55451E-01	0.0
8	18	-0.11000E+16	-0.17531E+00	0.0
9	19	-0.11000E+16	0.58453E-02	0.0
10	20	-0.11000E+16	-0.61657E-01	0.0
11	21	-0.11000E+16	0.71818E-01	0.0
12	22	-0.11000E+16	-0.12991E+00	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 3
                             SUBROUTINE "STRCNK"

DESIGN VARIABLES SPECIFIED:  PE,V,QS,N,DIA

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =    55.0000
                             DENSITY (LBF-SEC2/FT4)                =     1.9905
                             VISCOSITY (FT2/SEC)                   = 0.12817000E-04
                             ATMOSPHERIC PRESSURE (PSIA)           =    14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)=     0.2470

HULL PARAMETERS:             WAKE FRACTION                         =     0.2200
                             THRUST DEDUCTION FRACTION             =     0.1725
                             RELATIVE ROTATIVE EFFICIENCY          =     1.0250
                             NUMBER OF PROPELLERS                  =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =    15.0000
                             DIAMETER LIMIT (FT)                   =     0.0

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =        6.0
                             MATERIAL TYPE                         =  STAINLESS STEEL
                             ALLOWABLE STRESS (PSI)                =     5400.0

SELECTION VALUES:            PE (HP)                               =   21292.6
                             V  (FT/SEC)                           =   40.9171
                             N  (RPM)                              =  105.0000
                             QS (FT-LBF)                           =  1500607.0
                             PD  (HP)                              =  30000.05

                             ETAO SPECIFIED                        =     0.6527

                             J                                     =     0.8290
                             KT                                    =     0.2349
                             KQ                                    =     0.0448
                             ETAO                                  =     0.6915
                             REY75R                                =   0.3E+08
                             DIA (FT)                              =   22.0000
                             P/D                                   =     1.1813
                             AE/AO                                 =     0.7944
                             T/C .75R                              =     0.0754
                             BLADE WEIGHT (LBF)                    =   12842.6

CONSTRAINT VALUES:           MAX DIA (FT)                          =     0.0
                             MIN AE/AO                             =     0.8515
                             MIN T/C .75R                          =  0.069076

PROPELLER "POINTS":          PE DEVELOPED (HP)                     =   21168.1
                             V  (KNOTS)                            =   24.2400

                             QS REQUIRED (FT-LBF)                  =  1408084.0
                             N  (RPM)                              =  105.0000
                             PD REQUIRED (HP)                      =  28150.35
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	38
3	2

```
CCCCCCC   OOOOOOO   PPPPPPP   EEEEEEE   SSSSSSS
C         O     O   P     P   E         S
C         O     O   P     P   E         S
C         O     O   PPPPPPP   EEEE      SSSSSSS
C         O     O   P         E               S
C         O     O   P         E               S
CCCCCCC   OOOOOOO   P         EEEEEEE   SSSSSSS
```

C O N T R O L   P R O G R A M

F O R

E N G I N E E R I N G   S Y N T H E S I S

T I T L E

WAGENINGEN B-SERIES PROPELLER OPTIMIZATION

CARD IMAGES OF CONTROL DATA

```
CARD                      IMAGE

  1)  $A  TITLE
  2)     WAGENINGEN B-SERIES PROPELLER OPTIMIZATION
  3)  $B     NCALC       NDV        NSV       N2VAR     NXAPRX     IPNPUT     IPDB
  4)             2         3                                          0
  5)  $C    IPRINT     ITMAX     ICNDIR     NSCAL      ITRM      LINOBJ     NACMX
  6)             1      1000                   -1        30                    1
  7)  $C1     FDCH     FDCHM         CT     CTMIN       CTL      CTLMIN      THET
  8)          .001      .001       -.01
  9)  $C2  DELFUN    DABFUN     ALPHAX    ABOBJ1
 10)
 10)
 11)  $E    NDVTOT      IOBJ     SGNOPT
 12)             3         2       -1.0
 13)  $F       VLB       VUB          X      SCAL
 14)           0.2       1.1       1.00       1.0
 15)           0.4       1.4        1.3       1.0
 16)         0.003       0.5     0.0100     0.100
 17)  $G    NDSSGN     IDSGN      AMULT
 18)             1         3        1.0
 19)             2         7        1.0
 20)             3         9        1.0
 21)  $H     NCONS
 22)            12
 23)  $I1     ICON      JCON       LCON
 24)  $I2       BL     SCAL1         BU     SCAL2
 25)            11        11
 26)  -1.0     +16       1.0        0.0       1.0
 27)            12        12
 28)  -1.0     +16       1.0        0.0       1.0
 29)            13        13
 30)  -1.0     +16       1.0        0.0       1.0
 31)            14        14
 32)  -1.0     +16       1.0        0.0       1.0
 33)            15        15
 34)  -1.0     +16       1.0        0.0       1.0
 35)            16        16
 36)  -1.0     +16       1.0        0.0       1.0
 37)            17        17
 38)  -1.0     +16       1.0        0.0       1.0
 39)            18        18
 40)  -1.0     +16       1.0        0.0       1.0
 41)            19        19
 42)  -1.0     +16       1.0        0.0       1.0
 43)            20        20
 44)  -1.0     +16       1.0        0.0       1.0
 45)            21        21
 46)  -1.0     +16       1.0        0.0       1.0
 47)            22        22
 48)  -1.0     +16       1.0        0.0       1.0
 49)  $N
 50)  END
```

```
TITLE:
 WAGENINGEN B-SERIES PROPELLER OPTIMIZATION


CONTROL PARAMETERS:
CALCULATION CONTROL,                      NCALC =     2
NUMBER OF GLOBAL DESIGN VARIABLES,          NDV =     3
NUMBER OF SENSITIVITY VARIABLES,            NSV =     0
NUMBER OF FUNCTIONS IN TWO-SPACE,         N2VAR =     0
NUMBER OF APPROXIMATING VAR,             NXAPRX =     0
INPUT INFORMATION PRINT CODE,            IPNPUT =     0
DEBUG PRINT CODE,                         IPDBG =     0

CALCULATION CONTROL, NCALC
VALUE   MEANING
  1      SINGLE ANALYSIS
  2      OPTIMIZATION
  3      SENSITIVITY
  4      TWO-VARIABLE FUNCTION SPACE
  5      OPTIMUM SENSITIVITY
  6      APPROXIMATE OPTIMIZATION


* * OPTIMIZATION INFORMATION

GLOBAL VARIABLE NUMBER OF OBJECTIVE                =   2
MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) = -0.10000E+01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT  ITMAX   ICNDIR   NSCAL    ITRM   LINOBJ  NACMX1   NFDG
  1     1000      0       -1       30      0       15       0

 FDCH           FDCHM          CT              CTMIN
 0.10000E-02    0.10000E-02   -0.10000E-01     0.0

 CTL            CTLMIN         THETA           PHI
 0.0            0.0            0.0             0.0

 DELFUN         DABFUN         ALPHAX          ABOBJ1
 0.0            0.0            0.0             0.0

DESIGN VARIABLE INFORMATION
NON-ZERO INITIAL VALUE WILL OVER-RIDE MODULE INPUT
D. V.      LOWER           UPPER          INITIAL
NO.        BOUND           BOUND          VALUE            SCALE
  1     0.20000E+00     0.11000E+01     0.10000E+01     0.10000E+01
  2     0.40000E+00     0.14000E+01     0.13000E+01     0.10000E+01
  3     0.30000E-02     0.50000E+00     0.10000E-01     0.10000E+00

DESIGN VARIABLES
       D. V.      GLOBAL      MULTIPLYING
ID      NO.      VAR. NO.       FACTOR
 1       1           3       0.10000E+01
 2       2           7       0.10000E+01
 3       3           9       0.10000E+01

CONSTRAINT INFORMATION

THERE ARE 12 CONSTRAINT SETS
      GLOBAL   GLOBAL   LINEAR       LOWER           NORMALIZATION       UPPER
 ID   VAR. 1   VAR. 2     ID         BOUND              FACTOR           BOUND
  1     11       11       0      -0.11000E+16       0.10000E+01        0.0
  2     12       12       0      -0.11000E+16       0.10000E+01        0.0
  3     13       13       0      -0.11000E+16       0.10000E+01        0.0
  4     14       14       0      -0.11000E+16       0.10000E+01        0.0
  5     15       15       0      -0.11000E+16       0.10000E+01        0.0
  6     16       16       0      -0.11000E+16       0.10000E+01        0.0
  7     17       17       0      -0.11000E+16       0.10000E+01        0.0
  8     18       18       0      -0.11000E+16       0.10000E+01        0.0
  9     19       19       0      -0.11000E+16       0.10000E+01        0.0
 10     20       20       0      -0.11000E+16       0.10000E+01        0.0
 11     21       21       0      -0.11000E+16       0.10000E+01        0.0
 12     22       22       0      -0.11000E+16       0.10000E+01        0.0

TOTAL NUMBER OF CONSTRAINED PARAMETERS =    12
```

```
* * ESTIMATED DATA STORAGE REQUIREMENTS

           REAL                                INTEGER
INPUT   EXECUTION   AVAILABLE        INPUT   EXECUTION   AVAILABLE
 75        504        10000           49        112         1000
```

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 3
                             SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:  PE,V,QS,N,DIA

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                           =    55.0000
                             DENSITY (LBF-SEC2/FT4)                 =     1.9905
                             VISCOSITY (FT2/SEC)                    = 0.12817004E-04
                             ATMOSPHERIC PRESSURE (PSIA)            =    14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)     =     0.2470

HULL PARAMETERS:             WAKE FRACTION                          =     0.2200
                             THRUST DEDUCTION FRACTION              =     0.1710
                             RELATIVE ROTATIVE EFFICIENCY           =     1.0250
                             NUMBER OF PROPELLERS                   =        1.0
                             DEPTH TO SHAFT CENTERLINE (FT)         =    15.0000
                             DIAMETER LIMIT (FT)                    =     0.0

PROPELLER PARAMETERS:        NUMBER OF BLADES                       =        6.0
                             MATERIAL TYPE                          =  STAINLESS STE
                             ALLOWABLE STRESS (PSI)                 =     5400.0

SELECTION VALUES:            PE  (HP)                               =    17630.0
                             V   (FT/SEC)                           =    38.8240
                             N   (RPM)                              =   105.0000
                             QS  (FT-LBF)                           =  1500607.0
                             PD  (HP)                               =   30000.05

                             ETAC SPECIFIED                         =     0.5394

                             J                                      =     0.7866
                             KT                                     =     0.3212
                             KQ                                     =     0.0638
                             ETAO                                   =     0.6302
                             REY75R                                 =   0.8E+08
                             DIA (FT)                               =    22.0000
                             P/D                                    =     1.3000
                             AE/AO                                  =     1.0000
                             T/C .75R                               =     0.0100
                             BLADE WEIGHT (LBF)                     =     2563.1

CONSTRAINT VALUES:           MAX DIA (FT)                           =     0.0
                             MIN AE/AO                              =     1.0509
                             MIN T/C .75R                           =   0.056838

PROPELLER "POINTS":          PE DEVELOPED (HP)                      =    27514.5
                             V  (KNOTS)                             =    23.0000

                             QS REQUIRED (FT-LBF)                   =  2004649.0
                             N  (RPM)                               =   105.0000
                             PD REQUIRED (HP)                       =   40076.84
```

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                     *
*                  C O N M I N                        *
*                                                     *
*              FORTRAN PROGRAM FOR                    *
*                                                     *
*         CONSTRAINED FUNCTION MINIMIZATION           *
*                                                     *
* * * * * * * * * * * * * * * * * * * * * * * * * * * *

INITIAL FUNCTION INFORMATION

OBJ =    0.256313E+04

DECISION VARIABLES (X-VECTOR)
  1)    0.10000E+01  0.13000E+01  0.10000E-01

CONSTRAINT VALUES (G-VECTOR)
  1)   -0.45160E+00 -0.50840E+00 -0.36545E+02 -0.96245E+03 -0.50000E+00  0.
  7)    0.96987E-02 -0.24470E+00 -0.56066E+00  0.33589E+00  0.90655E-01  0.
```

```
FINAL OPTIMIZATION INFORMATION

OBJ =    0.104647E+05

DECISION VARIABLES (X-VECTOR)
  1)     0.77419E+00  0.10906E+01  0.66118E-01

CONSTRAINT VALUES (G-VECTOR)
  1)    -0.45160E+00 -0.50840E+00 -0.15063E+02 -0.98394E+03 -0.27419E+00 -0.
  7)    -0.48220E-01 -0.18658E+00 -0.24834E-02 -0.22189E+00 -0.25204E-02  0.

THERE ARE     3 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
     9    11    12

THERE ARE     0 VIOLATED CONSTRAINTS

THERE ARE     0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION
     ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR 30 ITERATIONS
     ABS(OBJ(I)-OBJ(I-1))   LESS THAN DABFUN FOR 30 ITERATIONS

NUMBER OF ITERATIONS =   46

OBJECTIVE FUNCTION WAS EVALUATED          102  TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED       102  TIMES
```

OPTIMIZATION RESULTS

OBJECTIVE FUNCTION
GLOBAL LOCATION 2 FUNCTION VALUE 0.10465E+05

DESIGN VARIABLES

ID	D. V. NO.	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	1	3	0.20000E+00	0.77419E+00	0.11000E+01
2	2	7	0.40000E+00	0.10906E+01	0.14000E+01
3	3	9	0.30000E-02	0.68118E-01	0.50000E+00

DESIGN CONSTRAINTS

ID	GLOBAL VAR. NO.	LOWER BOUND	VALUE	UPPER BOUND
1	11	-0.11000E+16	-0.49160E+00	0.0
2	12	-0.11000E+16	-0.50840E+00	0.0
3	13	-0.11000E+16	-0.15063E+02	0.0
4	14	-0.11000E+16	-0.96394E+03	0.0
5	15	-0.11000E+16	-0.27419E+00	0.0
6	16	-0.11000E+16	-0.25812E-01	0.0
7	17	-0.11000E+16	-0.48220E-01	0.0
8	18	-0.11000E+16	-0.16658E+00	0.0
9	19	-0.11000E+16	-0.24834E-02	0.0
10	20	-0.11000E+16	-0.22189E+00	0.0
11	21	-0.11000E+16	-0.25204E-02	0.0
12	22	-0.11000E+16	0.86784E-04	0.0

```
OPTIMIZATION RESULTS ------- DESIGN CASE NO. 3
                             SUBROUTINE "STRONK"

DESIGN VARIABLES SPECIFIED:  PE,V,QS,N,DIA

ENVIRONMENTAL PARAMETERS:    TEMP (DEG F)                          =   55.0000
                             DENSITY (LBF-SEC2/FT4)                =    1.9905
                             VISCOSITY (FT2/SEC)                   = 0.1281700004E-0
                             ATMOSPHERIC PRESSURE (PSIA)           =   14.7000
                             WATER VAPORIZATION PRESSURE (PSIA)    =    0.2470

HULL PARAMETERS:             WAKE FRACTION                         =    0.2200
                             THRUST DEDUCTION FRACTION             =    0.1710
                             RELATIVE ROTATIVE EFFICIENCY          =    1.0250
                             NUMBER OF PROPELLERS                  =       1.0
                             DEPTH TO SHAFT CENTERLINE (FT)        =   15.0000
                             DIAMETER LIMIT (FT)                   =    0.0

PROPELLER PARAMETERS:        NUMBER OF BLADES                      =       6.0
                             MATERIAL TYPE                         =  STAINLESS STE
                             ALLOWABLE STRESS (PSI)                =    5400.0

SELECTION VALUES:            PE  (HP)                              =   17630.0
                             V   (FT/SEC)                          =   38.8240
                             N   (RPM)                             =  105.0000
                             QS  (FT-LBF)                          =   1500607.0
                             PD   (HP)                             =  30000.05

                             ETAC SPECIFIED                        =    0.5394

                             J                                     =    0.7666
                             KT                                    =    0.2063
                             KQ                                    =    0.0372
                             ETAC                                  =    0.6950
                             REY75R                                =   0.3E+08
                             DIA (FT)                              =   22.0000
                             P/D                                   =    1.0906
                             AE/AO                                 =    0.7742
                             T/C .75R                              =    0.0681
                             BLADE WEIGHT (LBF)                    =   10464.7

CONSTRAINT VALUES:           MAX DIA (FT)                          =    0.0
                             MIN AE/AO                             =    0.7722
                             MIN T/C .75R                          =  0.068124

PROPELLER "POINTS":          PE DEVELOPED (HP)                     =   17673.8
                             V   (KNOTS)                           =   23.0000

                             QS REQUIRED (FT-LBF)                  =   1167640.0
                             N   (RPM)                             =  105.0000
                             PD REQUIRED (HP)                      =  23343.40
```

PROGRAM CALLS TO ANALIZ

ICALC	CALLS
1	1
2	103
3	2

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